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COAL USE BY THE NATION'S RAILROADS

HEARINGS

BEFORE THE

SUBCOMMITTEE ON
ENERGY AND MINERAL RESOURCES

OF THE

COMMITTEE ON
ENERGY AND NATURAL RESOURCES
UNITED STATES SENATE

NINETY-EIGHTH CONGRESS

FIRST AND SECOND SESSIONS

ON THE

REINTRODUCTION OF COAL AS FUEL FOR RAILROAD LOCOMOTIVES

ROANOKE, VA, NOVEMBER 28, 1983
WASHINGTON, DC, DECEMBER 20, 1983
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COAL USE BY THE NATION'S RAILROADS

MONDAY, NOVEMBER 28, 1983

U.S. SENATE,
SUBCOMMITTEE ON ENERGY AND MINERAL RESOURCES,
COMMITTEE ON ENERGY AND NATURAL RESOURCES,
Roanoke, VA.

The subcommittee met pursuant to notice, at 1 p.m., in room 403, Federal Building, 210 Franklin Road, S.W., Roanoke, VA, Hon. John W. Warner presiding.

Present: Senator Warner.

Also present: Roger Sindelar, counsel.

OPENING STATEMENT OF HON. JOHN W. WARNER, A U.S. SENATOR FROM THE STATE OF VIRGINIA

Senator WARNER. Today the Subcommittee on Energy and Mineral Resources studies the subject called, Reintroduction of Coal as Fuel for Railroad Locomotives. The Senate Subcommittee on Energy and Mineral Resources convenes to explore the reintroduction of coal for the rail. The hearing will focus on several aspects of burning coal in locomotives: the current status of research and demonstration projects, the outlook for this new technology, drawbacks and problems with coal-burning locomotives, and what, if any, is the appropriate role of the Federal Government in encouraging railroad locomotives to once again burn coal.

Experts have informed me in travels recently, particularly to a Federal facility up at Morgantown, WV, that in less than 2 years, the United States could be burning coal in its locomotives. I intend to do my very best to try and get to the bottom of these efforts and find out if this is a realistic goal and to the extent the Federal Government can properly assist these efforts.

I intend to accord this project a very high priority and personally allocate a considerable amount of time to the resolution of the many issues.

We all have an obligation to the many thousands of miners out of work and the inability of our coal industry to adequately compete in today's market. This may well produce another need for coal. We're going to get to that answer. It won't be today; I'm going to hold a second hearing and then I will have to assess the testimony and reach our own conclusions.

Until the late 1950's, coal was the principal power source of the Nation's railroads. We all remember the wonderful notes of the famed steam whistle as it raced through the Virginia countryside. Faced with the rising fuel costs in the 1950's, U.S. rails understandably converted to diesel fuel.

Today, somewhere between 35,000 and 40,000 U.S. railroad locomotives burn approximately 800,000 gallons daily or 4 billion gallons annually of diesel fuel.

With diesel fuel hovering around $1, this puts America's rail fuel bill at around $4 billion. With diesel prices again hovering around $1, fuel costs are of major concern. The race is on to see whether or not private industry, with some assistance from the Federal sector, can once again reintroduce coal as the fuel for the Nation's rail systems.

Preliminary estimates indicate that reconversion of all the Nation's rail locomotives to coal would lower rail fuel costs by as much as 50 percent and increase coal sales for the depressed coal industry by at least 20 million tons. Each ton of coal utilized by America is just that much less reliance on OPEC oil and furthermore, it will help our balance of payments.

These figures mean more competitive transportation rates, lower costs of goods to consumers, and thousands of jobs for U.S. coal miners and railroad workers.

Railroads are the economic lifeblood of our economy, transporting vital goods to every corner of the United States. In times of national emergency, the United States is even more dependent on our railroad transportation system.

The rail system, and I know this quite well being a member of the Senate Armed Services Committee, is part of the very foundation of our entire system of national defense. It would be catastrophic if we lost a major source of fuel by way of oil from troubles overseas in terms of our national defense obligation.

In 1981, diesel fuel burned by railroads represented 12.4 percent of the total U.S. consumption of OPEC oil. Because of the possibility of interruption of foreign oil supplies during national emergencies, the dependence of our national railroad system on imports of OPEC oil must be removed. The burning of coal by locomotives would reduce oil imports and release available supplies of diesel fuel for other national needs. This is vitally important for our Nation's economy, energy, independence, and, indeed even more important, our national security.

We have a distinguished group of witnesses here today representing the Federal Government, as well as the private sector, and they are working in various ways to try for the reintroduction of coal into the rail system.

As I mentioned we will have a second hearing, to be announced, and we study at that time the Jet Propulsion Laboratory Report and some of the Western rail systems will express their views. Indeed, I think the interest generated by this hearing will bring in maybe a little interest from other sectors.

Now, if these hearings establish a reasonable case for coal as a rail fuel then my job will be the following. First, to determine the extent to which the Departments of Transportation and Energy and other Government agencies and departments could add additional funding for research and development. Second, I would hope to draw up a piece of legislation providing for economic incentives and other incentives, maybe, in the way of taxes to see what we can do to let the private sector build the necessary prototypes, plants as well as locomotives, for modification of the existing diesel fuel. And then hopefully go into serious production.

I'm prepared to do what I can within my sphere as a U.S. Senator and member of the Senate Energy Committee, to get this job done. I thank those who braved the storm today to join me and others.

We'll ask as our first witnesses the members of the Department of Energy representing the Secretary. First, we will have Mr. Donald Bauer, Deputy Assistant Secretary—Fossil Energy, U.S. Department of Energy, Washington, DC, accompanied by Mr. John Wilson, Director of Coal Projects Management Division, Department of Energy Morgantown Technology Center, Morgantown, WV. Now, Mr. Bauer and Mr. Wilson, we will give you the time required. Your entire statement will be placed in the record and perhaps we would summarize some of the background material and hopefully represent here that this can be achieved as a goal within a reasonable period of time.

STATEMENT OF DONALD BAUER, DEPUTY ASSISTANT SECRETARY, FOSSIL ENERGY, DEPARTMENT OF ENERGY, ACCOMPANIED BY JOHN WILSON, DIRECTOR OF COAL PROJECTS MANAGEMENT DIVISION, DEPARTMENT OF ENERGY MORGANTOWN TECHNOLOGY CENTER AT MORGANTOWN, WV

Mr. Bauer. Thank you, Senator Warner. I am pleased to represent the Department of Energy today at this hearing. I might mention, Mr. Chairman, as you recall I had the privilege to appear before you at a similar hearing held in Blacksburg, VA. At that time, I also had the unfortunate timing to be out of the room when you asked a followup question regarding the Department of Energy's involvement in coal-fired locomotives and therefore I am especially pleased to be here today to have the opportunity to answer those questions, albeit some 3 months late. I appreciate that opportunity. I'm also pleased to have with me today, John Wilson, who was your guide when you recently visited the Morgantown Technology Center, to personally witness some of the work we are doing in the area of interest to this group and this hearing.

Senator Warner. If I might digress, it was my visit to the Morgantown Center and the information gained from that visit that generated this hearing. Congressman Boucher was with me and representatives of the Virginia coal company that began to spark the interest in this project. Indeed, you're partially responsible for this hearing and I hope that you will take a responsible role in the solution.

Mr. Bauer. As a preface to my testimony, Mr. Chairman, I might acknowledge the recent rate of increase within the railroad industry in returning coal to its role as a primary mover and a locomotive fuel source. I was quite pleased to read press accounts earlier this month when Norfolk Southern agreed to assist General Electric in financing a project to compare a nonpolluting, coal-burning diesel engine with other propulsion systems, and I look forward to hearing more about that today at this hearing.

From the Energy Department's perspective, I believe that the Nation's modern railroad industry—which benefits considerably from the movement of coal—is a prime market for converting back to coal use in a cost-effective and environmentally sound manner. To many of us in the Department, a key signpost of whether a technical concept is really valid is the willingness of industry to invest its own funds in a development effort. So, we've been pleased to see the recent initiatives within the rail industry.

Our efforts to assist industry in this regard are focused on establishing a suitable technologically sound data base in several related areas. I propose to focus my remarks today specifically on our coal-fired heat engine program and particularly the diesel application.

In my prepared statement, I have included background on the diesel industry as it exists today. Suffice to say that the diesel engine is one of the mainstays of our industrial sector with by far its major application being in the railroad industry.

The diesel engine, as we know it, is efficient, very compact, easily assembled and shipped, very reliable, cost-effective, and doesn't require substantial lead times for design and fabrication. I have two sons who are diesel mechanics, and they keep telling me I should switch to diesel driven cars.

However, like many of the power systems we have developed in this country during a period of cheap liquid fuels, the diesel has a major drawback: it is wedded to the use of clean distillate fuel.

Now, as the chairman is aware, it is extremely difficult to predict future patterns of energy supplies and prices. Some forecasts of the potential prices for distillate fuels are contained in our recently published National Energy Policy Plan. But these are simply projections and projections in the past have been frequently in error, and frequently the error has been on the low side.

So given these uncertainties on prices and possible supplies, I think it becomes incumbent upon those heavy users of these liquid fuels—like the railroad industry—to begin looking for new energy alternatives and to expand the range of acceptable fuels.

Also in my prepared statement I have described some of the various technological approaches that could better prepare the industry for the potential of long-term supply uncertainties and price hikes.

One approach is to squeeze more usable energy out of the fuels that are available to us. This is being done through the development of higher-temperature diesels. In these engines, combustion takes place at several hundred degrees hotter than normal, promoting more rapid and complete combustion. Several private sector firms are pursuing this approach, and the Department of Defense is funding some work in this area.

The approach which we are more interested in—and which, I believe is of more interest to this hearing—is the development of alternative fuels, particularly those based on coal. A considerable amount of work is underway here in the United States and in Europe to develop diesels which are compatible with lower quality fuels; by that I mean residual oil or synthetic liquids. But in recent years, the Energy Department, along with several private firms, has begun pursuing an alternative approach: the use of coal slurries, which are mixtures of coal and water predominently, although in some cases methanol is added to it.

The coal of that program is to produce a coal-based fuel that behaves much like oil. It flows like oil, has many of the same combustion characteristics, and can be burned cleanly.

If such a fuel becomes practical—and I believe that testimony that you will hear today shows that it is indeed a practical concept—then the advantage for the rail industry is an economic fuel based on coal that can replace petroleum as a fuel for the propulsion hardware of the locomotive.

For the coal industry the rewards lie in the potential for restoring an old market using cleaner, more efficient modern-day technology.

Prospects for achieving a high quality, fine particulate slurry have been hightened by recent developments, particularly in fine grinding and coal cleaning. Research has shown the technical feasibility of producing micron-size coal—that is coal much finer than talcum powder—that has an ash content as low as 0.1 percent. Also, the use of advanced chemical and physical coal preparation techniques that we are pursuing, including the application of ultrasonic grinding and microwave cleaning, offer the potential for major steps forward in the technology of cleaning coal.

Also, parallel advances are being made in slurry research. We have an aggressive program that addresses this fuel form, its characteristics, and its performance in a wide variety of end uses. The private sector has also taken much of the initiative to explore coal-slurry preparation and application concepts.

We are also doing work on the diesel engine itself and here our efforts are two-pronged.

First, under the Assistant Secretary for Conservation and Renewable Energy, coal slurry fuels are being evaluated in large, European designed and fabricated slow speed diesel engines. The principal application of these units is intended for stationary industrial cogeneration.

The program overseen by the Assistant Secretary for Fossil Energy, on the other hand, is aimed toward U.S. medium speed engines—that is, those engines that operate in a range from 300 to 900 r/min and are more widely used in the rail, tugboat, industrial, and utility sector. This activity is in its initial stages. It involves some of the work which you saw, Mr. Chairman, when you visited the Morgantown Energy Technology Center.

Specifically, we are evaluating the combustion and emission characteristics of premium quality, experimental slurry fuels under test conditions simulating those medium speed diesel applications. We are also examining the effect of these fuels on the engine parts—for example, the injectors and cylinder liners in the conventional engine configuration and in advanced, ceramic-lined, high-temperature engines.

I might, at this point, depart from my prepared testimony to mention two other technologies being sponsored by the fossil program that may be useful to the locomotive and transportation application. I refer to our work to develop a gas turbine capable of burning coal or coal-derived fuels and in fluidized bed combustion. The Department of Energy has recently undertaken a program to bring coal fuels to gas turbine engines. The technical problems are difficult, just as they are in coal-fired diesels, but the potential of using coal directly is a good incentive to pursue this technology. The major U.S. turbine manufacturers are involved in the DOE program, and interest has continued to build for this technological area. Fluidized bed combustion of raw coal, even poor quality coal, is a near commercial technology especially in the size of interest to the locomotive use. The problem is in packaging of the boiler in the size and shape for a practical locomotive. You will hear today about one such concept being pursued by a company that was an early participant in the DOE fluidized bed program. This technology, I believe, has the potential to remove some of the impediments in returning coal use to locomotives, namely sulfur oxide and smoke emissions.

These are areas where we believe the Government has an appropriate role in establishing a data base of generic information from which companies like G.E. and Norfolk & Southern can draw for use in their own development efforts.

In conclusion, Mr. Chairman, I believe the emergence of a new array of technological concepts—coupled with uncertainties in the future prices and supplies of conventional liquid fuels—has led to a resurgence of interest in the coal-fired rail system.

Our job at DOE is to determine if modern-day technological advances have improved the prospects for coal to enter this sector of the market. We are working on the advanced concepts necessary to make that determination: premium quality fine coal advanced fuel forms and advanced engine designs and materials required to burn those fuels in heavy-duty engines.

If a solid foundation of technological knowledge can be established, then we believe industry will be properly positioned to take the next steps to apply that technology.

Mr. Chairman, I thank you. That completes my comment. I would be pleased to answer any questions you would have or to call upon Mr. Wilson.

[The prepared statement of Mr. Bauer follows:]

Testimony of Donald L. Bauer
Principal Deputy Assistant Secretary
for Fossil Energy
U.S. Department of Energy
to the
Subcommittee on Energy & Mineral Resources
Senate Committee on Energy & Natural Resources
November 28, 1983

Thank you, Senator Warner. I am pleased to represent the Department of Energy at today's hearing on the use of coal by the nation's railroads. I am accompanied today by John Wilson, the director of our Coal Projects Management Division at our Morgantown Energy Technology Center who can answer the more technical questions concerning our research program.

As a preface to my testimony, Mr. Chairman, I might acknowledge the recent increase in interest within the railroad industry in returning coal to its role as a primary locomotive fuel source. I was quite interested to read press accounts earlier this month when the Norfolk Southern Corp. agreed to assist General Electric in financing a project to develop a nonpolluting, coal-burning diesel locomotive.

From the Energy Department's perspective, we believe that the nation's modern rail industry -- which benefits considerably from the movement of coal -- is a prime market for reverting back to coal use in a cost-effective and environmentally-sound manner. Within the Department, a key signpost of the validity of a technical concept is the willingness of industry to invest its own funds in a development effort; so, we have been pleased to see the recent initiatives within the industry.

Our efforts to assist industry in this regard are focused on establishing a suitable, technologically sound data base in several related areas, including coal-fired heat engines such as diesels and turbines; coal-slurry combustion and characterization; and coal beneficiation. Each of these could provide valuable data to the rail industry in its efforts to substitute increasing amounts of coal for higher-cost premium fuels.

My testimony today will focus principally on coal-fired diesel power although I will touch briefly on some of the related technology efforts.

Background

Diesel engines serve a variety of industrial and commercial power generating applications in the U.S. Rail, waterway, and road transport systems depend on diesels for a major share of their power needs. Utilities also make extensive use of diesel power to provide peak surges of power when demanded. Rural power generating capacity is frequently based on diesel systems. Industry uses diesels to supply a significant portion of its electric power, and increasingly, to combine electric generation witn the production of process heat in "cogeneration" systems.

Approximately 40,000 diesel engine units, totaling nearly 90 million horsepower, currently serve U.S. electric utilities, basic industries, railroads, and inland waterway and marine shipping interests. Rail transport comprises by far the major share of this total, nearly 70 million horsepower. Inland and offshore water transport represents about 14 million horsepower, while the remainder, nearly 4 million horsepower, is used for generating utility or industrial power. In total, these units consume the equivalent of more than 1.2 million barrels of oil per day.

The diesel cycle has captured these markets because it offers inherent efficiencies -- as high as 42 to 50 percent for several modern industrial and utility engines. There are other important advantages too: the diesel is compact; it can be shop assembled, shipped, and installed as a single unit; it adjusts well to load variations; it is reliable; its capital costs are relatively low (approximately $250/horsepower for medium speed units); and it can be put into service relatively quickly with minimal lead-times for design and fabrication.

A competitive, well-founded diesel manufacturing, marketing and service structure is already well established in this country and is capable of implementing economically-sound technological advancements without major changes or disruptions.

The principal obstacle in the future of diesel power is the cost of fuel. Domestic diesel engines depend primarily on clean distillate fuel. The future cost of this fuel is uncertain, but according to some projections, it could rise over the next two decades from approximately $7 per million Btus (1980) to nearly $12 per million Btus (also 1980 dollars) in the year 2000.* Assuming that total diesel fuel consumption increases from the current 2.5 quads (quadrillion Btus) to the 5.5 quads now projected for the year 2000, the cost of fuel to U.S. diesel operators could be nearly $76 billion (1981 dollars) -- almost twice what they spent in 1981.

The Association of American Railroads (AAR) reports that class 1 railroads alone consumed 4.1 billion gallons of diesel fuel in 1981. The AAR notes further that average diesel fuel prices rose from 10.73 cents per gallon in 1970 to nearly 10 times that amount -- to $1.04 per gallon -- in the first quarter of 1981. Notwithstanding the current relative stability in world petroleum markets, some analysts, both within the Department and the railroads, believe that prices could return to a long-term growth trend in the future with supplies uncertain at best.

In response to both problem areas, i.e., the projections of escalating energy costs, particularly over the longer-term, and the uncertainty regarding future supply, the AAR is, among other approaches, exploring the feasibility of expanding the range of acceptable fuels for locomotive propulsion.

Technological Approaches

There are several possible responses to the long-term uncertainties regarding diesel prices and supplies. Improved efficiency is one. The technical feasibility of this approach has been demonstrated in U.S. Army tests of an experimental high temperature, so-called "adiabatic", diesel engine in a 5-ton truck. In this diesel concept, combustion takes place at several hundred degrees hotter than normal, promoting more rapid and complete combustion. The Department of Defense, along with several private sector firms, are following this developmental path.

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*Based on projections of the National Energy Policy Plan - 1983

Another approach is to develop engines that can accept alternate, lower quality liquids fuels, such as residual oil or coal-derived liquids. Before these fuels find widespread acceptance in the diesel power industry, however, problems in the combustion characteristics and in the effect of impurities such as ash have on engine wear must be solved. Research efforts both in private and government laboratories in the U.S. and Europe are addressing these problems.

European operators are using residual oil in large slow speed engines which are inherently more tolerant of lower quality fuels than the medium and high speed engines that are predominant in the U.S. The AAR and other private sector and Federal programs (e.g. the Department of Transportation) are attempting to modify engine design and operating factors which would permit use of specifically defined residual and coal-derived liquid fuels.

The DOE Program

The current program within the Department of Energy is looking beyond these nearer-term applications to the longer range, potentially higher payoff use of coal slurry fuels. Considerable attention was given first within the Federal program to coal-oil mixtures; the focus has now shifted to coal-water and coal-water-methanol mixtures -- or in other words, finely ground coal that has been suspended in either water or a combination of water and methanol. Additives are often used to enhance handling and to minimize settling.

The goal is to produce a fuel that can be handled like a liquid and thus do away with the front end complexity of coal yards and on-site preparation equipment. If coal-slurry fuels can be developed and applied economically, the simplicity of the liquid fuel infrastructure would be preserved.

For the diesel power industry, including the railroads, the potential rewards of the successful development of coal-slurry fuels are twofold: (1) economic, assuming that a clean slurry fuel would cost less than residual or crude oils, and (2) strategic, that is, the capability of reducing dependence on scarce petroleum supplies should a future national petroleum shortfall occur. For the coal industry, the rewards lie in the potential for restoring an old market using cleaner, more efficient modern-day technology.

For both, achievement of these goals will depend upon the nature and quality of the coal-slurry fuel.

Prospects for achieving a high quality, fine particulate slurry have been heightened by recent developments, particularly in fine grinding and coal cleaning. Research by the Energy Department and the private sector has shown the technical feasibility of producing micron-size coal -- coal much finer than talcum powder -- with ash contents as low as 0.1 percent (which requires, for some coals, more than 99 percent ash removal). The use of advanced chemical and physical coal preparation techniques, including the application of ultrasonic grinding and microwave cleaning technology, offer the potential for major steps forward in the technology of cleaning coal.

Parallel advances are being made in slurry research. The Energy Department has an aggressive program that addresses this fuel form, its characteristics, and its performance in a wide variety of end uses. The private sector has also taken much of the initiative to explore coal-slurry preparation and application concepts.

Combining these technologies could ultimately produce a combustion engine quality fuel at a cost significantly less than conventional distillate fuel.

The Department's diesel combustion program is a two-pronged effort. Under the Assistant Secretary for Conservation and Renewable Energy, coal slurry fuels are being evaluated in large, European designed and fabricated slow speed diesel engines. The principal application for these units is intended mainly for stationary industrial cogeneration.

The program overseen by Assistant Secretary for Fossil Energy, on the other hand, is aimed towards U.S. medium speed engine service (300-900 RPM), more widely used in rail, towboat, industrial and utility service. This activity, which is conducted at our Morgantown Energy Technology Center, is in the initial stages.

Specifically, researchers working in the Fossil Energy program are evaluating the combustion and emission characteristics of premium quality, experimental slurry fuels under test conditions simulating the operating regime of medium speed diesel service. At the same time, they are studying the effect of these fuels on the engine parts -- namely, the fuel injectors and cylinder liners in conventional engine configuration and in advanced ceramic lined adiabatic engines.

Conclusion

Coal and the railroads have long possessed an interdependency that is vital to the interests of both. Yet, with the exception of the research performed for the Locomotive Development Committee and Bituminous Coal Research in the 1950s (which involved the use of coal in gas turbines), little work has been done in recent times to reestablish the railroad industry itself as a market for coal. Today, this appears to be changing.

The emergence of a new array of technological concepts, coupled with uncertainties in the future prices and supplies of conventional liquid fuels, has led to a resurgence of interest in the coal-fired rail system. The diesel engine is an integral component in the modern-day rail industry and therefore, represents a prime candidate for the application of these new technologies.

The technical feasibility of burning coal dust in diesel engines was studied in Germany more than fifty years ago. Technical problems hindered much of the early research. Our job today at DOE is to determine if modern-day technological advances have improved the prospects for coal to enter this sector of the market. We are working on the advanced concepts necessary to make that determination -- premium quality fine coal; advanced fuel forms, especially slurries; and advanced engine designs and materials required to burn such fuels in heavy duty engines.

If a solid foundation of technological knowledge can be established, then we believe industry will seize the initiative to commercialize the technology as economic and market forces dictate.

Thank you, Mr. Chairman.

Senator WARNER. Thank you, Mr. Bauer. I would like to introduce my associates, Mr. Sindelar, who is counsel for the Subcommittee on Energy and is a member of the Energy Committee staff of the U.S. Senate. And Ms. Magill is on my staff and devotes her time largely to the subject of energy. I might add that Ms. Magill is a native of Roanoke. That might say why we're here today. No, we selected Roanoke because it's the gateway to the coal country and one of the great rail centers of this part of America.

Now, let's get down to some rockbottom figures. Diesel fuel is about $1 a gallon today. What could a plant produce today in an amount of this coal slurry mixture that could be usable in the locomotive that's currently on the rail today? I think I'll reverse the question. Let's go down to the yards right here in Roanoke and take a diesel engine. First, how much modification would we have to perform on that existing diesel engine to inject today's technology in coal slurry?

Mr. WILSON. I suspect there would be a fair amount of modification to that particular diesel engine. In fact, it may not even be practical to use coal slurry in an existing design diesel engine. It would probably be very feasible to design a diesel engine that would fit in that same chassis to use coal as its principal fuel.

Senator WARNER. So the first point of modifying the existing fleet is not an alternative?

Mr. WILSON. It would probably be better to ask some of the locomotive manufacturers but my opinion would be it would not be an alternative.

Senator WARNER. So we start from scratch with a newly designed locomotive to use the coal slurry. What's the cost of that per gallon?

Mr. WILSON. I'm not sure I can give it to you on a cost per gallon but it's probably in the order of half the cost of diesel fuel at this point so if your number is $1, maybe 50 cents a gallon. But you have to look at a million Btu's of fuel going in as the criteria in the volume.

Senator WARNER. Let's do it on the Btu basis, then.

Mr. WILSON. Diesel fuel is probably $7 to $8 per million Btu's and again, you have a coal company who could maybe address this better than I. Probably a slurry of finely ground coal could come in at half that price: $3.50 or so per million Btu's. It seems to be an achievable goal.

Senator WARNER. Of course that's dependent on the investment capital in the plant that would produce this?

Mr. WILSON. That's certainly true.

Senator WARNER. Would that require any subsidization, or could you go ahead and build that plant and bring it in on a Btu basis for roughly half of what diesel fuel is today?

Mr. **Wilson**. That's my estimate, yes.

Senator **Warner**. And that's based on what data base to date, in the Federal Government? How much research? How much time? How much in the way of Federal expenditure in dollars to develop that conclusion?

Mr. **Wilson**. Well, we haven't spent very much money in the Federal sector on the very premium quality slurry fuels that would be necessary for the gas turbine and diesel engines that might be applicable to the locomotive service. The program is very new and we've spent probably 2 years and a few million dollars in that research activity at this point. It is a logical extension of a program that's been in place for some time to use coal-water slurry fuels in boilers which is a much less severe kind of an application.

Senator **Warner**. Now, the ash content. You said 0.1 percent. You've achieved that through several processes?

Mr. **Wilson**. There are coal cleaning processes that are at very small scale, very experimental and developmental that we have, in fact, achieved ash levels in the 0.1 to 0.3 percent of ashes.

Senator **Warner**. Now, is that a figure that would be acceptable by mechanical engineers in terms of wear and tear inflicted on the moving parts of a newly designed locomotive?

Mr. **Wilson**. Well, that's part of the program that we're now undertaking. We're looking at the qualities of the fuel and the engine as well to see how the two marry themselves together. But yes, the manufacturers of engines are saying the same to us and that's why we're establishing those limits.

Senator **Warner**. So they are acceptable. You really have a mechanical engineering problem and the fuel problem and they've got to be in parallel.

Mr. **Wilson**. That's right.

Senator **Warner**. It is interesting that a Member of the Senate, Jennings Randolph of West Virginia, actually flew on an airplane in 1940–41 using fuel from coal. My understanding is that there was so much ash in it that eventually that engine would not have had a very long lifespan. Isn't that correct?

Mr. **Bauer**. But that was a liquid fuel, which had been distilled.

Senator **Warner**. It was distilled, so it didn't have an ash content?

Mr. **Bauer**. No; it didn't.

Senator **Warner**. But that was one of the problems, the ash content of the slurry?

Mr. **Bauer**. Yes.

Senator **Warner**. And you think that you, in research and development, have enough data today to say that we can go ahead on the expenditure of the redesign of these engines because we can bring that ash content down to levels of tolerance acceptable by the mechanical engineers?

Mr. **Bauer**. We've done enough research in our coal preparation program on physical and chemical coal cleaning, to know we can get the ash level down. Dr. Wilson's program says if you get down to 0.1–0.3 percent and you get the mechanical engineers with the combustion engineers, they will help us determine if that is an acceptable level or do we have to go lower? That's the focus of our program.

Senator **Warner**. I admit to being a newcomer in this area. I guess I'm astonished by the amount of research and development money that's gone into this problem. You said several millions of dollars. Compared to what we put into some of our national defense programs in the hundreds of millions of dollars, when we've got a potential cost recovery for this country of maybe 50 percent of just rail fuel costs, the amount spent on R&D does not seem to be that great. Has the Government been shortsighted in its research and development program here? I know I'm putting you on report a little bit with your bosses, but do the best you can. I mean, you've got a $4 billion fuel bill with just the rail system of America, in terms of diesel fuel, and if you can lower the fuel bill by half, it would seem to justify a bigger program.

Mr. **Bauer**. Let's just take the coal program which is generally 80 percent of our fiscal year appropriations. We have said that our main concentration in fiscal year 1984 is to make maximum use of the resource that we have most of—coal. Given that premise, then what the Assistant Secretary and I have done is put our priorities on the front end to the back end of the coal fuel chain—coal cleaning, combustion, and cleanup. Once we had that piece of strategy, then we got the headquarters managers together with our field managers and said, what are our priorities and where do we get the most return on our investment considering the fact that we have our in-house research at the ETC's, the national labs, universities, and the private sector. What we have elected to do is to marry all of that together and talk to all four parties to assure that we complement each other's activities. Because we don't want to be doing something which the private sector says they don't have any use for in their own in-house research. Now, this takes time to get to that point. And also, is anyone in the private sector willing to cost share or work with us or make some type of commitment? And that's what we've done. It's taken maybe a year to a year and a half to get there in our heat engine program. But that's what we're doing now and I think we're really getting a big return on the dollars appropriated for it. It takes a lot of time and energy. You've got to do a lot of interface and coordinating. Just like John got the turbine manufacturers and the people that make the slurries together. We must take the time and marry it all together and then you can come up with a viable program. In the diesel program within our heat engine effort, we're only spending a million dollars in fiscal year 1984 but we've going to have a return on that investment in 1984.

Senator **Warner**. How much research is being done in the private sector? I know that's hard to quantify but compare it with what the Federal Government's doing. A relatively equal amount or greater or less combined?

Mr. **Bauer**. With the recent announcements, I'd say the private sector is probably five times that.

Senator **Warner**. Five times what Uncle Sam's doing?

Mr. **Bauer**. Yes.

Senator **Warner**. What about State government? Is Virginia doing any? West Virginia?

Mr. **Bauer**. I am not aware of any. The only one that I'm aware of is we have some work at the universities in the State but they are not funding such research on their own.

Senator **Warner**. So basically Uncle Sam and the private sector are the only entities that are doing research on this locomotive.

Mr. **Bauer**. Yes, sir.

Senator **Warner**. And to some extent the educational institutions are doing some R&D on this matter. What is the amount being spent by the Nation's universities on R&D in this area?

Mr. **Bauer**. We're funding most of the universities.

Senator **Warner**. You're doing most of the funding?

Mr. **Bauer**. Yes.

Senator **Warner**. Could you use some more funding next year? I know you're leaving here to go up and participate with your Secretary in budget hearings. Keep in close contact with me, for a variety of reasons but especially on the progress you make on your budget hearing as I pass on his budget.

Mr. **Bauer**. Yes, sir.

Senator **Warner**. One of the questions I'm going to hit him with when he takes the witness stand next February is whether there's enough money going into this type of research. Just prepare him for that question.

Mr. **Bauer**. I'm going back to receive our passback from OMB for the fiscal year 1985 budget. I guess one could say that like the research people in the private sector, we never get all the research dollars that are needed. But I think that we have put together for 1985 a technically defensible program. We have made some assumptions of what the private sector activity is going to be. Just a moment ago we talked about the 5-to-1 ratio. If there is a large enough market, if the technology is promising, if the work that we are doing is not at a scale sufficient for the private sector to take that risk, then there is an appropriate role for the Government to advance that technology to that state of development. We will just have to wait and see the results of the fiscal year 1984 research program and yes, we will be having our budget hearings in February, March, and April. Our Morgantown center is starting to get some coal slurry mixtures of very fine size with very small ash content. They are doing the chemical analysis now; they will be doing some combustion testing soon. We will get the results of those tests and I would say about February or March we will know whether the moneys that we're asking for fiscal year 1985 are sufficient enough to do the job to help put coal back into the marketplace, particularly in the rail industry. So I'm not evading the question, Mr. Chairman. I think in the next 90 days we're going to have some data analysis which will give us an indication.

Senator **Warner**. Can the goal of reintroducing coal for the rail system be divided into two basic parts? One, the manufacture of slurry, and two, the manufacturing of a new type of locomotive to handle the slurry? Is that an oversimplified way of dividing the problem? Now, of the two parts, which one is the most advanced in your judgment and how far ahead is it of the other?

Mr. **Wilson**. I would suspect that slurry manufacturing is a leg up and that is because of the beginning interest in the commercial use of slurry in boilers. The engine people have not gotten very serious about it. We're beginning to sow some seeds there. I think there's probably 4 to 5 years of development work on the engine itself.

Senator WARNER. Four or five years? Wait a minute, now. I was told it could be a little less than that.

Mr. WILSON. There are several ways you could work the technology into locomotives. There are technologies you can use today, and I think you are going to hear about one of those that would use a more conventional furnace or boiler. If you're talking about using a coal-fueled diesel or gas turbine, then you're further downstream by a couple of years.

Senator WARNER. So the slurry part of the equation is ahead of the engine part. That leads me to the next question and that is financing a prototype engine. Would you be prepared to recommend to your secretary that Government look at a program by which to finance one or more prototypes. When I say one or more I think we should take a look at several different types, and we will hear about several today.

Mr. BAUER. I guess it would all depend, Mr. Chairman, on what scale or prototype that private sector was proposing. If it was of a sufficient scale which would allow proof of the technical feasibility of that concept, then we have made a general determination that that's where Federal role should end. For example, we're doing work on indirect liquefaction, at 35 barrels per day where on direct liquefaction the technical feasibilty is being shown at 6 tons per day. We have established a scale where we think the Government role should end. I guess it would all depend on the private sector participant—what scale he's proposing, what amount of cost sharing that he would be willing to spend and hypothetically, if he would come to us* * *.

Senator WARNER. Let's talk about a life-size engine. I think we would probably want to build one, wouldn't we, to prove this thing? I say life size, one that could go and integrate with the existing rail systems and pull a train to prove its feasibility.

Mr. BAUER. I'm not sure that if we do the testing at the scale that is available today that you can take that quantum jump or that large of a jump straight to the full-scale locomotive diesel. I'm just not sure you can do that.

Senator WARNER. I guess I'm losing you.

Mr. BAUER. What Detroit did when it did the diesel engine was to take the old internal combustion engine which is much lower in temperature pressure, and they tried to make a diesel engine out of it. And that's why, 3 or 4 years ago, we had all the problems because the engine could not take those temperatures and pressures. If you start building a prototype diesel engine for locomotive application today, I'm not sure that you want to go all the way to build a full-sized locomotive and put in your slurry mixtures. I think you would want to have an intermediate stage to have a basis for doing your analysis and establishing the feasibility. It is very expensive to run a very large size engine. We learned that in the synfuels program, and I came into the Department of Energy when we were in the demonstration plant business. Every demo plant always had a very small-scale pilot plant behind to serve as the basis for generation of data or solving the problems with the larger unit. That was proven to be valuable in the synfuels program and I think it would be valuable in this instance. But we're going to have to wait and see what suppliers and people are coming to us.

Senator **Warner**. I think that's a very carefully drafted response and we'll have to turn to the engineers.

Mr. **Bauer**. Yes. And that's what I look forward to hearing today. And I think in the next 90 days, as I said a moment ago, what we find out is going to be the key to this.

Senator **Warner**. The next 90 days. Why the next 90 days?

Mr. **Bauer**. Because we're going to have, I think, in talking to the people involved in John's program—the diesel program—he's starting to get some of the slurry mixtures now with the right ash content to do some analysis and some burn tests which will be an indicator of erosion and corrosion on the internal components. That will give you an indicator of what percent ash that you can tolerate. You get that data and go back to the mechanical people. What we're doing now is laying out that program plan. You lay out a 3- or 4-year program for this type of thing. And one fact we hope to learn after talking to the manufacturers—the people that build engines—is what size they are interested in building. Part of the cost sharing may be an offer of inkind contribution. The proposer would provide the fuel or whatever else. So we'll have to see what the nature of cost sharing is, and what size of tests are proposed because they must be at a scale which the private sector is willing to scale up and take the risk.

Senator **Warner**. What's the cost of a new diesel engine?

Mr. **Wilson**. $1 million.

Senator **Warner**. $1 million in the Department of Defense—they lose that much every 5 minutes.

Mr. **Bauer**. $1 million, to me, is very important.

Senator **Warner**. I know that but what I want to impress upon you and others is that we're looking at two things here. A possible reduction of the Nation's fuel dependence in billions of dollars and we're looking at national defense. We've got to get rolling! Now, you mentioned foreign interests. Where are we, the United States, in R&D compared to some of the other nations? Germany, for example, has always had a strong technology base in diesel work and, of course, they've been interested in coal.

Mr. **Wilson**. Yes, indeed. The foreign work that Mr. Bauer mentioned is being done by Seltzer which is a Swiss company that makes slow speed diesels. They have run several tests burning powdered, slurried coal in a diesel engine for short periods of time. They have had reasonable success and they have been working for 3 or 4 years in that activity. The German work that was done back in the 1911 to 1930 time period was also in slow speed diesels, very mammoth size engines. They had a number of technical problems, and the technology was put on the shelf and never completed. I don't know whether they're doing much at this point.

Senator **Warner**. Would you say the United States is preeminent in the R&D field, in this area?

Mr. **Wilson**. In terms of steam diesel engines and gas turbine engines, yes, I think we are.

Senator **Warner**. What about the environmental considerations of this new slurry mixture in locomotives?

Mr. **Wilson**. There are a couple of reasons for trying to prepare premium quality slurry fuels. One of the reasons is to allow the engine to operate on the fuel. And the other one is to deal with some of the environmental concerns. If you reduce the ash levels and you also reduce the sulfur levels, you can take care of some of those problems. We're also examining the application of environmental cleanup devices that were never included in the old coal-fired engines.

Senator **Warner**. Well, in very general terms, I'll leave it to the rail experts, but my recollection is that one of the inducements to go to diesel on the American rail system was the advancement in the Nation of environmental concerns. Where will we be, say, on this environmental curve with the new coal-fired locomotive? We had steam in the late 1940's, we've now got diesel and now we're coming along with coal slurries. Where in there will we find ourselves? In other words, presumably with diesel we were better off in terms of environmental problems then we were with coal-fired steam engines. Now we come along with, let's say, the third generation engine, with major propulsion systems on the Nation's rail system—coal slurry—will it be better than diesel in terms of environmental impact?

Mr. **Bauer**. I don't think we would tolerate being worse.

Senator **Warner**. As a nation?

Mr. **Bauer**. Either we can equal the diesel performance——

Senator **Warner**. We can equal or better and still bring in that 50-percent Btu cost? Remember, that's the target.

Mr. **Bauer**. That's right.

Senator **Warner**. That completes the questions that I have. But I'm going to do something a little unusual here. Senators can take a little leeway. We have a group of witnesses who offered to come here and help us today. Any of the witnesses have a question or two that they'd like to put to the Federal Government representative? Now is the opportunity. Rarely done in a hearing but I'm prepared to do it. Hearing silence, I would commend you on your testimony. You've apparently covered the subject quite adequately in the minds of not only the chairman and my colleagues here, but the other witnesses. As I understand it, you will stay for a while this afternoon but you do have to go up to the budget hearing.

Mr. **Bauer**. Thank you, Mr. Chairman.

Senator **Warner**. On behalf of the Senate Energy Committee, I thank you.

We will now invite Mr. Hobart Scott, vice president of the Norfolk and Southern Corp., and he will be accompanied by Mr. Hanes of General Electric Co.

STATEMENT OF HOBART SCOTT, VICE PRESIDENT, NORFOLK & SOUTHERN CORP., ACCOMPANIED BY C. W. HANES, DISTRICT MANAGER, LOCOMOTIVE MARKETING DIVISION, GENERAL ELECTRIC CO.

Mr. **Scott**. Thank you Senator. I am pleased to appear before you today to present my views on the subject of coal use by the Nation's railroads and more specifically the potential for the use of coal as locomotive fuel. This subject has been of particular interest to me during my career with Norfolk & Western Railway Co.

Senator WARNER. I think it would be helpful if you sketched your career. How many years in railroading?

Mr. SCOTT. Well, since 1950 with Norfolk & Western and now with Norfolk & Southern. And that time has been spent almost half-and-half in operations and locomotive power and locomotives. I had some part in the last improvement of the reciprocating steam engines on the Norfolk and Western.

Senator WARNER. They were phased out about when, 1950?

Mr. SCOTT. In the mid-fifties. And I was on loan to coal research in the early fifties on the coal-fired gas turbine project. I spent about 3 years on Norfolk & Western's coal-fired steam turbine project.

Senator WARNER. Which was for locomotive power?

Mr. SCOTT. Yes.

Senator WARNER. Done in the late 1950's, to my recollection?

Mr. SCOTT. It was on the railroad between 1954 and 1957. And then I've had experience with coal-fired electric generating plants for straight electric locomotives on a couple of our mountainous sections of railroad in years past. And so, this subject has been near and dear to my heart.

Senator WARNER. Would you say you're a qualified expert witness?

Mr. SCOTT. No, I said it was near and dear to my heart. There are three principal reasons of which you've touched upon a couple in your remarks, but at least three principal reasons that my company is keenly interested in the use of coal by railroads. First, the substitution of domestic coal for foreign oil as locomotive fuel would have a most favorable effect on our balance of payments. It would make our Nation stronger, more self-reliant to decrease our dependency on foreign oil and frankly would give the railroads a decided business advantage in the event of another oil shortage for whatever reason. Second, as major U.S. coal haulers, the Norfolk Southern companies are continually encouraging the expansion of existing coal markets and the development of new markets which can be of benefit to our shippers and to the transportation industry. Third and finally, the further development of coal-burning technologies hopefully will lead to decreased costs, operating costs for the railroads and thereby improve our efficiency and productivity.

Senator WARNER. And it would help the export business which has impacted heavily by rail and transportation costs?

Mr. SCOTT. Right. The cost of diesel fuel today represents a substantial part of the railroads operating budget.

Senator WARNER. What would that rough figure be?

Mr. SCOTT. For us, about 9.4 percent for the first 8 months of this year.

Senator WARNER. That's annualized. Roughly, 10 percent ballpark?

Mr. SCOTT. Well, the annualized figure came out 9.4 percent of our operating budget. And so, if an economical alternative to diesel fuel can be developed, we may be able to lower our operating costs.

The key is not simply to have an alternative but to have an economical alternative. The Norfolk & Eastern Railway, for many years ending in the early 1950's, designed and built right here in Roanoke the most modern and efficient coal-burning reciprocating steam engines ever built in this country. As you probably know, we were the last major U.S. railroad to convert from coal-burning steam engines to diesel engines.

Senator WARNER. You might give us a little history of why America's rail system was driven to the diesel?

Mr. SCOTT. Well, we had an alternative to diesel fuel obviously, we were running coal-burning steam locomotives. But we did not have an economical alternative. And we had to convert to diesel engines in order to stay competitive.

Senator WARNER. In other words, the price of diesel fuel in say 1955—that was about your last operating year that comes to me.

Mr. SCOTT. Right.

Senator WARNER. Was it such that the coal was more expensive or the overall coal and the maintenance of the engine?

Mr. SCOTT. It's the overall operating cost for the locomotive. The fuel cost is only one factor and you have your maintenance costs and your ownership costs. Being the last operator and builder of steam locomotives, we were faced with such things as not being able to acquire appurtenances such as pumps, compressors, those sorts of things that we were not set up to build and had to buy on the outside.

Senator WARNER. So the subcontracting infrastructure was fading out because of the lack of demand nationally?

Mr. SCOTT. That's correct. Now I don't want to create a false impression here that had we been able to continue to procure those items we would still be building steam engines because that's not correct. The maintenance costs on the diesel is much less than on the steam locomotive, a reciprocating steam locomotive, and the ownership costs are less because you have to have fewer locomotives because of higher availability.

Senator WARNER. Now let's get that point. In other words, what we call downtime of the old reciprocating steam engine was considerably greater than downtime for the diesel locomotive for regular annualized maintenance?

Mr. SCOTT. That's exactly correct.

Senator WARNER. And what about the unit cost of the diesel versus a comparable steam reciprocating unit right there in the 1950's?

Mr. SCOTT. In the 1950's, I'm trying to remember now. Had we in the 1950's been able to remain exactly status quo at that particular time, the cost was about comparable.

Senator WARNER. They were about comparable then?

Mr. SCOTT. Yes. But today, even though the price of diesel fuel has increased eight or nine times from what it was in the mid-1950's, the former Norfolk & Western modern efficient reciprocating steam locomotive would still not be an economical alternative to diesel today.

Senator WARNER. And one of the main reasons is the downtime of that reciprocating engine versus the diesel? What about the manpower? Is the manpower requirements for the two engines the same?

Mr. SCOTT. It was still about the same crew at that time. Of course, now there would be a difference. However, the tractive-effort characteristics of a reciprocating steam engine are inferior to any electric drives. A diesel electric, straight electric, turbine electric, whatever, has tractive characteristics that are much more favorable to handling trains, to starting heavier trains, and to getting over grueling grades and that sort of thing. That's another reason that it takes less units with electric drive than with straight reciprocating drive.

Senator WARNER. And what about the environmental conception?

Mr. SCOTT. Well, obviously the steam engine of the early 1950's caused more environmental pollution than a diesel engine. There's no question about that. However, that was not a driving force to the conversion in the 1950's.

Senator WARNER. Of your system or nationwide?

Mr. SCOTT. In our system.

Senator WARNER. But nationwide, in some of the more populated areas?

Mr. SCOTT. Could have been. In addition to designing and building its own coal-burning steam engines, I indicated to you at one time that Norfolk & Western had two coal-fired electric generating plants that supplied power to a straight electric locomotive on two mountain sections of the present lines. At the end of their economic lives, both of these coal-burning electrification projects gave way to more economical modes. The first one being a major grade improvement and modern coal-burning steam locomotives in the 1940's and the second one gave way to diesel engines in the 1960's. But as railroad electrification has advanced, as the technology has advanced in the intervening years, both the Norfolk & Western Railway and the Southern Railway have made repeated feasibility studies, both in-house and through the use of outside consultants, attempting to justify the electrification of portions of their lines. And in each case, the high cost of money and the high initial costs of these electrification projects have ruled out a favorable recommendation. Technically speaking, the less risk to get coal back on the rail by electrification than any other thing that I know of. But we can't afford it.

Before converting to diesel engines——

Senator WARNER. To go to rail by electrification would mean the erection of a plant to generate and then you've got the transmission lines and then you've got a whole new loco unit?

Mr. SCOTT. And an overhead catenary to carry the current.

Senator WARNER. Yes, the transmission. So that's a big capital investment of three parts—engine, overhead transmission, and initial generating plant?

Mr. SCOTT. That's correct.

Senator WARNER. And when you figure all that out, you can't deliver?

Mr. SCOTT. You can't justify it.

Senator WARNER. Can't justify it?

Mr. SCOTT. Can't justify it. Wish we could. I was starting to say that before finally converting to diesel engines that's when the Norfolk & Western made every effort to keep coal as its primary locomotive fuel. And in addition to improving the design and modifying its own steam locomotives to increase utilization and efficiency. Norfolk & Western was in the forefront in efforts to develop a coal-fired gas turbine locomotive and a coal-fired steam turbine electric locomotive. The gas turbine effort was funded by the Norfolk & Western and eight railroads and coal companies and headed up bituminous coal research. And this gas turbine concept failed primarily because of unsolved technical problems which caused the turbine blades to be eroded away rather quickly by the products of combustion that went directly through the turbine. Now the development of the coal-fired steam turbine electric locomotive was a tripartite undertaking with the Norfolk & Western Railway, Babcock and Wilcox Co., and Westinghouse Electric Corp. The prototype locomotive was assembled by Baldwin Locomotive and received extensive inservice tests on the Norfolk & Western, about 3 years' worth. While the steam turbine concept was technically feasible and proved to be such, the saving in fuel costs, when compared to diesel engines, was not sufficient to overcome the higher initial cost, lower availability, and higher maintenance costs of the steam turbine locomotive.

Senator WARNER. The steam turbine locomotive would have, say, an old type boiler box on it?

Mr. SCOTT. No; it was an old type. It was the first water tube boiler applied to a locomotive. It was 600 pounds pressure, 1,000 degrees total temperature.

Senator WARNER. Is that the same concept that is found aboard a naval ship? The 600-pound plant that we've got on Navy vessels?

Mr. SCOTT. Yes, sir. In fact, the controls on it, on that particular locomotive, were the first commercial application of a control system on the nuclear sub, the *Nautilus*, that was released about that time.

Senator WARNER. So you took that, generated steam and then you shot that steam into a conventional turbine?

Mr. SCOTT. Yes.

Senator WARNER. Which turned the generator, made electricity, and the electricity went into your drive mechanism?

Mr. SCOTT. That's correct. Again, we had an alternative to diesel fuel, but not an economical alternative.

Senator WARNER. You couldn't work it out and that was in what year?

Mr. SCOTT. 1957 when we finally retired that locomotive.

Senator WARNER. 1957 when diesel fuel was 10 times less or a tenth of what it is today?

Mr. SCOTT. It's eight or nine times more today, yes.

Senator WARNER. Now, supposing that unit were down here in a museum. Could you haul it out and make it economical today?

Mr. SCOTT. No.

Senator WARNER. Couldn't do it?

Mr. SCOTT. No sir.

Senator WARNER. Why not?

Mr. SCOTT. Not that particular unit.

Senator WARNER. I mean just hypothetically, if it were ready to roll out and operate as if did in 1957 with 10 times the cost of diesel fuel. I'm trying to take that unit with 10 times the cost of diesel fuel today and see where we are.

Mr. SCOTT. The initial cost of that particular unit, if we had to buy it versus the initial cost of comparable horsepower in a diesel and the maintenance on the two units. The operating costs of locomotives three main parts, the fuel, maintenance, and ownership costs, and they'll run roughly a third each. But the savings in fuel simply was not sufficient to offset the other two.

We have continued to follow technical and economic developments that might lead to restoring coal as the primary locomotive fuel on this Nation's railroads and we believe that now is the time to try again to accomplish this most worthwhile objective. We have been particularly encouraged by some on-going research being headed up by the General Electric Co. and have recently reached agreement with that company to contribute a million dollars toward the continuation of those research activities.

Senator WARNER. If I could interrupt here. What is the basic line of research today—I'm probably anticipating what you are going to say—versus what you did in that 1957 unit?

Mr. SCOTT. The 1957 was the coal-fired steam turbine locomotive.

Senator WARNER. And that was your last venture into R&D in a big way?

Mr. SCOTT. That's correct.

Senator WARNER. And what are you doing differently today than you did in 1957?

Mr. SCOTT. The objective of the particular program that we have with the General Electric Co. is to identify in the light of the present technology, the coal-burning locomotive concept that has the greatest likelihood of being successful in making coal an economic alternative to diesel fuel and thereby restore coal as the primary fuel for railroad locomotives. There are no strings attached. All we are saying is we want a coal-burning locomotive and whether that's a coal-fired gas turbine electric unit or a diesel unit that burns coal or some other concept, we will be just happy to get coal back as the primary fuel. Now, we think—this is just our thoughts—that the prospects to our coal-burning gas turbine electric locomotive have been greatly enhanced since our last developmental efforts. And we think that a prototype locomotive using this concept could become a reality in the next 4 to 5 years. However, if our research shows another coal-burning locomotive concept to be more favorable, we would support such a concept and be equally enthusiastic about it.

In summary, I guess I can say that Norfolk Southern, and its operating subsidiaries have been, and continue to be, staunch supporters of those efforts having reasonable prospects of success in making coal an economical alternative to diesel fuel for railroad locomotives. And we very much thank you and we appreciate very much your interest in this matter as well as those others testifying here today.

Senator WARNER. Mr. Scott, you've helped me a great deal to understand the problem better and you can handle testimony quite skillfully with interruptive questions. Let me go straight to several things—what kind of government help, Federal Government help, do you think should be offered or, frankly, not be offered to further this project along?

Mr. SCOTT. I think the proper incentives for the private sector to do this job—I'm talking of incentives in the way of tax incentives on research and development——

Senator WARNER. That probably is in the legal department and would you submit that question to your colleagues and come back with an answer? Because I respect you as an engineer and you don't like them meddling in your business and maybe they'd like to come up with those tax incentives. But you need some economic incentives?

Mr. SCOTT. Certainly, whatever they are.

Senator WARNER. You said 4 to 5 years. As you can obviously see, I'm a little impatient. Do you think we have to go through the interim scale-up system of a small stationary plant and then to a modest size, maybe rolling, and then—how soon do we get to that prototype before—maybe not a whole unit train the first time but some real coal cars? What are the steps? If you were in charge of the R&D, how would you move?

Mr. SCOTT. It will depend a great deal on the results of this program that we are in now of determining the concept we want to follow. There are probably fewer technical problems insofar as getting a full-scale engine going. Probably fewer technical problems with the coal-fired gas turbine electric than with the other concepts. Now, that's one man's opinion. To develop a new diesel engine that will burn some sort of coal slurry fuel probably has more problems than the gas turbine taking that sort of fuel.

Senator WARNER. Do you agree with the prior testimony that we couldn't take your rolling stock today and change it in some manner and modify it probably to take some sort of coal slurry mixture?

Mr. SCOTT. From what I know about it, no, I don't think that can be done.

Senator WARNER. So the rolling stock, as we know it today, would just have to be phased out in an orderly procedure and the evolution of coal returning to rail to new engines, bottom to the top?

Mr. SCOTT. I'm afraid that's correct.

Senator WARNER. You mentioned you're going into a partnership, so to speak—well, anyway whatever the legal thing is—with GE to the tune of $1 million. Do you know of anything parallel to that R&D in the Federal Government? In other words, you're taking your corporate revenues to do a project that might well be done by other revenues?

Mr. SCOTT. Well, obviously we have access to this information through various Federal Registers and publications and what not. We know of the work being done with DOE and others and the FRA. As I say, we are particularly encouraged with this work that GE is doing and wanted to be sure that it did continue.

Senator WARNER. Mr. Scott, thank you very much.

Now we will hear from General Electric.

STATEMENT OF C. W. HANES, DISTRICT MANAGER, LOCOMOTIVE MARKETING DIVISION, GENERAL ELECTRIC CO.

Mr. HANES. I'd like to take this opportunity to apologize for Bob Weeks who was supposed to be here today. His flight was canceled in Washington. So I do have a short prepared statement that I would like to present in Bob's behalf.

Senator WARNER. Well now, Bob Weeks, for the benefit of those in attendance, is manager, product planning and market research, locomotive division of GE.

Mr. HANES. Correct.

Senator WARNER. So he is the gentleman, presumably, with the greatest degree of corporate knowledge on the subject. We will accord him the opportunity to come to the second hearing. But we are pleased that you took the time to come here to present a brief statement on his part.

Mr. HANES. Being headquartered here in Roanoke it was convenient. General Electric Co. manufactures diesel electric and straight electric locomotives at our plant in Erie, PA, for domestic railroads and for export to railroads throughout the world where trade barriers do not preclude our marketing participation. We are the free world's second largest locomotive builder. I appreciate the opportunity of appearing before this committee to offer comments on the possible use of coal as a fuel for railroad locomotives. Fuel is a very major component of railroad operating costs currently running in excess of $3.5 billion annually and accounting for some 13.6 percent of freight service expenses in 1981. General Electric Co. has been working intensively to improve the fuel efficiency of its locomotives. Those being delivered today are up to 20 percent more fuel efficient than those shipped just 10 years ago. And those we'll be shipping 2 years from now will be even more efficient. While we are not at the end of the road further improvements becoming increasingly difficult and the continuing use of diesel fuels leaves the Nation and its railroad system with a premium fuel cost vulnerable to price and availability uncertainties which we all recognize. On the other hand, coal in addition to being a domestically produced secure source of energy offers an opportunity to reduce both dependence on foreign oil and the balance of payments deficits. At the same time, and of great importance to our railroads, coal currently ranges from 50 cents to $1.50 per million Btu's at the mine mouth versus No. 2 diesel fuel which is about $6 per million Btu's. So coal has the potential for significant savings in fuel costs. A number of our railroad customers have expressed interest in exploring with us the feasibility of a locomotive which derives all or a major part of its energy from coal. As a result, the transportation system business operation at General Electric Co. undertook a study beginning last March to validate the feasibility of coal as a fuel substitute and the type of locomotive best suited for its use. Agreements associated with the purchase of new General Electric locomotives by two railroads, the Norfolk Southern headquartered in Norfolk and one of the largest coal hauling railroads in the country, and the Burlington Northern, similarly a large coal hauler in the Western United States, will enable us to devote broad resources of General Electric to this project. While the project is being directed by the transportation system business operation of Erie, other components of General Electric such as our corporate research and development center in Schenectady, the gas turbine and steam turbine businesses and aircraft business group will all participate toward achieving this objective. This work is expected to take about 2½ years at assessed technical and economic issues including impact on railroad infrastructure associated with both steam and gas turbines as well as diesel engines. Fundamental to any of the alternatives is that the results meet railroad requirements in terms of reliability, availability, maintainability, and performance as well as being environmentally acceptable.

For this first phase of the program, we do not expect to produce production design or to do full-scale engine tests. Also, outside the scope of the study, are reciprocating steam locomotives and such long-term possibilities as sterling cycle engines and fuel cells. We believe the scope of this feasibility study with the varied resources we have brought to bear and with the help of major railroads such as Norfolk Southern and Burlington Northern provides a sound approach to its ultimate achievement of the successful coal-burning locomotive.

Senator WARNER. Thank you very much. As far back as March, your corporate setup recognized the need for its customers to reexamine this concept of burning coal for locomotive power. You sell engines to how many different rail systems?

Mr. HANES. Well, to all the major railroads in the United States and to many foreign countries.

Senator WARNER. There are only two engine builders as I understand it in the United States, GE and GM?

Mr. HANES. Right.

Senator WARNER. Well, that's quite interesting. So independently you've arrived at the same conclusion that I have, that we'd better take a look at this thing.

Mr. HANES. I think that is correct, right.

Senator WARNER. We thank you very much. At this time, I would like to introduce Mr. Price. Mr. Price is vice president of Federal affairs of the CSX Railroad. We thank you, Mr. Price, and it is my understanding that you may wish to submit for the record, a statement.

Mr. PRICE. Yes, sir. And thank you for asking me to be here as an observer. I'm inclined to agree with our principal competitor, Norfolk Southern, to honor CSX's commitment to exploring every possibility for the use of coal as a source of fuel for locomotives. Also, we are a major coal hauler, as you know, and support any increased use of coal.

Senator WARNER. Would you concur in Mr. Scott's very colorful way of saying "now is the hour" and we should reexamine this option of going to coal?

Mr. PRICE. Yes, sir, we are. A later witness will indicate that we have participated through the Chessie Systems subsidiary in looking at one option.

Senator WARNER. Thank you very much, Mr. Price.

Mr. Strayer, we thank you for coming up today.

STATEMENT OF JOHN STRAYER, DISTRICT MANAGER, EASTERN DIVISION, ELECTRO MOTORS DIVISION, ATLANTA, GA

Mr. STRAYER. My name is John Strayer and I represent Electro Motors Division of General Motors Corp., which is the largest builder of locomotives.

Senator WARNER. Oh, are we having a competition here? You can settle that on your own turf.

Mr. STRAYER. We are very much interested in alternative fuels and we do have alternate fuel programs underway at this time. Both Electro Motors Division and General Motors Corp., for not only locomotives but for many types of vehicles. Many of the things stated today, adiabatic engines—we are undergoing research at the present time. We've done a considerable amount of research in the last several years on alternate fuels from methanol derived from coal and we are burning methanol in some countries in the world today in our locomotives. And we are also undergoing a research program at the presen time to burn natural gas in locomotives and other diesel engines. There are many other scenarios which we are working on. General Motors has perfected the sterling cycle engine which is an external combustion engine for many years, from different types of power sources. That is being looked at. And our interest is not only related to the economics of the American railroads but also to the strategic welfare of the United States in the event of a national energy crisis like we went through before which cuts off the liquid fuel supply. And we, as a major supplier to the railroads, will be in the forefront in research in alternate fuels. And we do not care to reveal any of the programs that are undergoing at the present time but coal-fired locomotives is one of the scenarios that we're looking at, two or three different versions. So we are very much interested in it. We also, at the same time, are looking at the end product and, of course, we have to be competitive in the performance of the locomotive and the reliability of the locomotive, the initial cost, the facility and handling investment involved with coal, and also the complexity of the product. So we are very much interested in the coal-fired locomotive and are undergoing research at the present time.

Senator WARNER. Your competitor, GE, indicated a number of their clients urged them to begin to look at these alternative fuels. I presume you have a parallel experience?

Mr. STRAYER. That's correct.

Senator WARNER. I guess its the cart and the horse that they or you started first. But it is a concerted effort by both of you. Your clients and your own in-house R&D.

Mr. STRAYER. Yes.

Senator WARNER. GE has a working relationship with one of our major rail systems, Norfolk Southern. Do you have any working relationships with any of your users or purchasers?

Mr. STRAYER. Not at the present time. We have several research facilities. The Pure research facility is run by the corporation in Warren, MI, which we use. We've also done research with an Allison Division which is the gas turbine division of the corporation. I would say the General Motors concept is pretty much in-house. We have our own research and development activities.

Senator WARNER. Among the various alternatives of fuels would you put coal at the top so far in the way the numbers are working out?

Mr. STRAYER. I'm not sure where it lies. I think at this point in time they are reviewing all of the scenarios to look at the liquid fuel derived from coal, which is coal slurry, versus powdered coal. You might have read in the magazines and newspapers about the powdered coal gas-fired turbine automobile that General Motors has been designing and working on for many years. There is a working model at the present time that is operating. So I think that you have to look at all of the alternatives and then look at the bottom line as to which is going to be the most reliable. Most cost effective. I don't think we are prepared at this time to say which one is.

Senator WARNER. Where do you believe you are in your cycle of R&D toward the next generation of locomotives? Putting aside refinements in the diesel system which, they say, is making progress in making the diesel more efficient.

Mr. STRAYER. There has been and in fact there's a tremendous amount of R&D going into present locomotives because, well, we have 40,000 diesel engines running in the size range in the world and they have a life of approximately 20 years. They cannot be scrapped immediately. They have to—it's too expensive. So they will be running a long time. We are doing a lot of R&D and have made substantial improvements in fuel efficiency. As a for instance, the modern-day locomotive such as an SD40 locomotive is the mainstay of the American fleet. From 1977 to 1985 we have made an approximately 20-percent improvement in the fuel economy. And there is continuing R&D to bring that down further. And we are undergoing many of those programs because these fuel economy features—many of them can be retrofitable to existing locomotives. We have a program today to retrofit the existing locomotives with the most fuel-efficient components that we've designed today. That's undergoing. And there's even more research. We're not stopping the research on the present model at this time. I would say these alternate fuel sources are down the road 4 to 5 years. We are also doing research today on heavy fuels, blended fuels. We are operating engines with these heavy fuels at the present time.

Senator WARNER. What's a typical example of a blended fuel?

Mr. STRAYER. There are many different blends. Some research, I believe, was done a year or so ago by a major railroad using 90-percent heavy fuel.

Senator WARNER. What's the definition of "heavy"?

Mr. STRAYER. Diesel. And the heavy fuel would be a No. 6 grade fuel. The blend was a 90-percent diesel and 10 percent heavy fuel. And as you go down the ladder, you get to 80-20 and so forth. But before that's an economic alternative to what we have today there has to be quite a bit of research done.

Senator WARNER. Are you prepared to advise the committee on whether or not you could blend coal in with diesel? Has anyone tried that?

Mr. STRAYER. It can be done. I'm not exactly sure of the amount of research we are doing in that area.

Senator WARNER. I'd like to explore that. If any of the subsequent witnesses can address that issue, I would be very much interested in it.

I think that pretty well covers your testimony and I thank you very much.

We will now hear from Dr. Richard Wolfe, vice president of research and development, United Coal Co., Bristol, VA.

I must say that Dr. Wolfe is the type of optimist that I like. He and one other gentleman are responsible for this hearing taking place and I want to acknowledge my appreciation on behalf of the Committee on Energy for your encouragement to have this hearing.

STATEMENT OF DR. RICHARD WOLFE, VICE PRESIDENT, RESEARCH AND DEVELOPMENT, UNITED COAL CO.

Dr. WOLFE. Thank you, Senator. I'm somewhat motivated because I'm with a coal company and we do, indeed, need to find new markets for our coal.

One of the markets that looked like the most reasonable and the most easy to achieve with regard to coal conversion is the application into a diesel locomotive market. The synfuels efforts that we initiated here in Virginia several years ago required billions and billions of dollars to build a large plant in order to make large quantities just to be able to put it into commercialization. I think the diesel application, either marine diesel or locomotive diesel, do not require a major expenditure of billions of dollars to build a plant just to run one engine. If we can transport coal from the coal fields to Norfolk back and forth with one train, one engine a number of times, I think we can prove and establish this concept. Then I believe you can have the economics all proven with a lower capital cost than what's required say, in a large major synfuels effort. That's why we're encouraged about this new area. It's certainly not a new area, it's time that coal got back to what we lost in the 1950's to the oil business. And one of the ways that we're trying to approach that at the United Coal Co. is to look at how we can make coal such a convenient fuel as clean as we possibly can with oil so that there's little modifications to the engine. That's the one primary goal.

The second goal would be to make a major retrofit of engines. We have, over the last 4 years, been working in this area of coal conversion. And if you're looking at the price we're talking about today, 85 cents to a dollar a gallon for diesel. That's about $7 to $8 a million Btu. That equates to about $200 a ton for coal.

Senator WARNER. What is coal selling for today?

Dr. WOLFE. Thirty-five dollars a ton if you can get that. So here we're talking five times more expensive. And if you're talking about in 1950, the switch to diesel was to 25-percent lower cost. We're talking 500 percent more expensive to use diesel fuel. So if we can find a way to spend $100 a ton just to put it into a form that the diesel locomotive could be used, we could still save the rail industry something like $30 a ton, or 30 percent of their fuel costs. Now 30 percent, if you say Norfolk & Western or CSX would use $500 million a year in fuel costs, you're talking something on the order of $100 million in energy savings. That's significant. That can build a number of plants to do this. This is why I think it's so interesting to put this particular specializing market in focus. I think it can be achieved without a major cost. I think we do need greater Government participation than what we heard this morning. I do believe we need to have a major initiative out of the Department of Energy to spend more money in this area. That will encourage more private companies like ourself, as a coal company, like those people here—the other witnesses—to spend their money. I think the Federal dollar can be the catalyst to help focus on this one particular area.

What are the next steps that we need to take? Right here in Virginia our company is now making a major effort to set up a small manufacturing plant with our own dollars to manufacture about a half-ton to a ton-an-hour fuel that can be used in a test program. Now, this facility we're going to build will be down in Bristol, VA, and we will then be able to do the research associated with the micronized coal, the super cleaning of coal that you saw at Morgantown. And again, this is an effort for industries trying to find some new ways and we, as a coal company, are trying to take the lead along with other coal companies to find new markets for our coal.

I wanted to show a few slides, if I could, that will just show you a little bit about what United Coal Co., is doing to put these programs in perspective and then kind of summarize.

This is last December down in Bristol. There is some pretty country here in these mountains of Virginia and this is our corporate headquarters down in Bristol, VA.

This is a major preparation plant—and it looks like I've got it backward—this is over in Grundy, VA. I think you've seen that preparation plant. But this is a preparation plant that processes from 700 to 1,000 tons an hour of coal for the utility market. As we would see the application of developing this kind of fuel, you would adapt the preparation plant we have here or others like it that exist to make this special fuel, rather much like a refinery in which you have different grade products coming out. By doing that and integrating it into this plant, you reduce greatly the capital costs. So when people mentioned this morning $3 to $4 to $5 per million Btu's, yes, I believe that's achieveable. I believe we can make a coal-water mixture or a liquid coal fuel form that is less expensive than diesel today. And use our facilities here where instead of rail cars we might have tank cars coming out as well.

This here is another view of a rather modern adaptation of our plant. You see the large circular disc. This, at one time, was a very fine coal that used to be thrown away. We at United Coal Co., are recovering this superfine coal and now processing that coal. Now that coal is already 90 percent ground to something like less than 100 mesh size, which means it will be the primary feed to go into a manufacturing of coal-water mixture or superclean coal. So you've already got the facility in place.

Here is an example of some superclean coal that we prepared for the Department of Energy. This particular small sample here has coal on the order of 0.3 percent ash.

Senator **Warner**. Now, how have you taken that ash out?

Dr. **Wolfe**. Well, a number of different ways. Primarily by physically cleaning it. Cleaning it down with various different levels of specific gravity that would float off the coal and sink the ash. A flotation process.

Senator **Warner**. Was the 0.01 of 1 percent figure used by the Department of Energy officials achieveable in your judgment?

Dr. **Wolfe**. I think it is. Within reason, within a reasonable price.

Now, on a large scale, I think that you would have to make some major modifications. There needs to be more research in that area. But remember, we've got a lot of dollars here to work with to be able to clean that coal.

This is a large voiler where we're starting already to do some testing and modifications in the coal-water mixture fuel.

Here is a test loop, a coal-water slurry that we're pumping and liquid coal. So this shows the type of research that is ongoing down in Bristol that demonstrates the flowability of this liquid form. And I'd much rather use this liquid form for coal understandably.

Here's a test loop we have in our facility where we are pumping it from round and round and we pumped it for miles to check the viscosity and the stability and how the coal holds up under different types of conditions.

And again, here is the different types of grinding techniques that one uses to make some of this superfine clean coal. These technologies did not exist 10, 15, 30 years ago. But these are the new technologies now that make this a much stronger base than what we've had in the past to make a liquid coal that has application in new markets.

Again, this is a sophisticated type of atomic adsorption unit to measure and trace elements in the coal. We are able to measure the various parts per million that would cause corrosion in pistons. We understand that better than we did 30 years ago.

Again, this is another type of drying system and cleaning system that we've been developing within our own plant to clean coal and physically clean the coal of its ash particles.

And here's a liquid coal base. A couple of months ago we were fortunate to receive from the Department of Energy a couple of grants to make a coal-based fuel. This is a liquid coal fuel that we've made that has no water in it. And its a 100-percent coal-based fuel much much cheaper than say a synfuels product that has the same characteristics. In fact, it has the characteristics that you can light it with a match, which is very similar to oil.

Those slides, I think, demonstrate what the technology is today and where its going. So in summary, I do believe that we have the basis now to develop coal into new markets. I think the locomotive diesel market is certainly one. I think the marine diesel market is another, as well as stationary power diesel market. So these are the areas. Once you've developed this coal, we can approach these types of markets. I believe it will open up a whole new area. And it would be a much smaller way but less expensive way to demonstrate these new marketable costs.

Thank you very much for this opportunity and I'm very pleased to be here.

Senator **Warner**. I certainly express the appreciation of the committee for your interest in this subject and your knowledge. Its helpful to get the private sector perspective. Now, you've worked a good deal with the West Virginian Federal Center there in Morgantown. I expect you've had as many trips up there as any member of the private sector. Do you wish to make any comments on the level of Federal funding? Understandably, the representatives today were rather circumspect. They have to answer to their bosses and are unable to comment to much on the budget at this point in the process.

Dr. **Wolfe**. Well as you know, Senator, I was also with the Department of Energy about 5 years ago. When I did leave I left in order to get back into the private sector so that we could do some things in the private area to supplement the Government. I believe that the right initiative to reduce Federal spending is a proper initiative. However, I think we've got to set priorities in our country with regards to our total energy. The Fossil Energy Program, in my opinion, has been cut too far with respect to, say, the nuclear program. The whole total Department of Energy budget has been reduced, which I support. But I don't believe its proper to cut the coal program and increase the nuclear program. And that's exactly what's happened here and I think our priorities are wrong in that respect. I think the coal fossil program should have the nuclear budget—just switch them around. So certainly I believe if we had more initiative from the Federal Government it would accelerate the application of the coal into these special markets. A good example is that the coal budget has been cut by about 70 percent from what it was 4 years ago and the nuclear budget has been increased by about the same amount. So I just think we have our priorities that need to be reevaluated with regard to our energy picture in this country. And certainly I believe if you had more money at Morgantown, you could absolutely achieve a much greater acceleration of this program.

Senator **Warner**. What about Federal subsidizing of the prototype program? I regard that as relatively modest sums of money, in comparison to my other major area of responsibility, namely, handling the biggest piece of the research and development budget for the Department of Defense. This prototype program would be extraordinarily modest, with an amount of Government contribution being very minimal. And yet, it seems to me that it is just as important to the national defense to have a measure of energy independence from OPEC as it is to have a new tank program.

Dr. **Wolfe**. I think the biggest problem we have in this country today is that we're paying large dollars out of our country for imported oil. I don't mind the use of imported oil but we have to pay dollars for it and now every dollar that goes abroad, that goes overseas, we lose it from our economy. If we could circulate it back into our economy, its worth three or four times what it would be if we paid it out of the country. And I definitely believe if it takes some tax subsidy, we can absolutely achieve that and you'll put people back to work. You'll put coal miners back to work and you'll put industry back to work here in this country.

Senator **Warner**. Having had some experience in the Department of Energy in the very area which we are addressing today and having listened to the testimony are you willing to go out on a limb with me and see if we can beat that 5-year time?

Dr. **Wolfe**. Absolutely.

Senator **Warner**. You think we can do it?

Dr. **Wolfe**. I believe that we can.

Thank you very much.

Senator **Warner**. Mr. Prahl, we welcome your participation today.

STATEMENT OF FREDERICK A. PRAHL III, PRESIDENT, NATIONAL STEAM PROPULSION CO., WOBURN, MA

Mr. **Prahl**. Thank you very much for the chance to testify today.

Our firm was founded about a year ago for the purpose of developing a coal-fired locomotive essentially based on repowering the existing diesel locomotive. One of our cofounders is the Wormser Engineering Corp. that manufactures a fluidized bed system to burn coal which is used in this locomotive.

Senator **Warner**. Now you used a key phrase and that is repowering "existing" diesel locomotives. The testimony thus far has been somewhat discouraging on taking the existing rolling stock and doing modifications. But you're here to address the possibility of a modification?

Mr. **Prahl**. We do think its possible. This is just a little bit about the economics as we see it. This is aside from the security aspect of being on coal. Basically, you'd analyze fuel and when you're talking about coal, you know, cost per million Btu's, the energy content of coal and the cost vary so much you want to be able to combine the two parameters to the one parameter, so the cost per million Btu is a way to do that. Of course, in diesel fuel its present constant in heating value so its directly proportional—the cost of diesel fuel is directly proportional to cost per gallon. At 90 cents per gallon diesel fuel is about $6.50 per million Btu. An average value for coal which can be fired in this system is about $1.35 per million Btu. Now the energy use is there, you have to figure both the cost and the energy used. Diesel, of course, is very fuel efficient for oil and its about 60,000 million Btu per year whereas a steam locomotive of the type that we're talking about—this is a full fired steam locomotive—is about half as energy efficient. However, because the fuel differential was almost 5 to 1 in this case, the cost are quite different for fuel, as you can see; $380,000 about for oil versus about $160,000 for coal. Assuming and calculating the other operating costs, the maintenance and operating costs came from the Department of Energy report that was done by JPL so that the total operating costs for the diesel we've estimated at fuel plus $68,000 per year and fuel costs $110,000 for the coal-powered locomotive. Cost of fuel depot as we see is about $1 million per year in order to provide a coaling depot for the system.

CAPITAL COSTS.

Diesel SD50 or C36-7 are about $1.2 million and our system, we think, is a new locomotive will be on the order of $1.6 million.

Payback here is shown as the function of the cost per million Btu in coal and between $1 and $2 per million Btu. You have a payback in the range of 2 to 4 years.

This is the annual savings per locomotive. This is a simple payback curve without the time value of money or the tax implications. It shows a breaking point of about 2½ years.

SPECIFICATIONS

This is shown on SD45 or SD50 chassis but any six-axle unit of 3,000 horsepower or more could be used as the basis for our powerplant. So its a 3,500 horsepower unit with a 12 cylinder steam engine. A small cylinder reciprocating steam engine actually build on a diesel engine block. The boiler is a Wormser grate fluidized bed system. The total weight of the system of the locomotive alone is 382,000 pounds. The weight of the tender supply to the passive unit rather than a slug would be about 300,000 pounds.

Senator **Warner**. Let me get this clear in my own mind. Somehow I had the impression that you wanted to take rolling stock out of the roundhouse down here and do a little reshaping and put it on the rails.

Mr. **Prahl**. To some extent that is possible. Let me show you the next picture. That might help you to understand.

Senator **Warner**. All right.

Mr. **Prahl**. This is a layout of a locomotive design. This is on an SD50 chassis. The key thing here is that all the components from the altimeter on through the rest of the system are the same as existing diesel. What we've done is to replace the diesel engine with a small cylinder reciprocating steam engine and the Wormser grate fluidized bed combustion system. Now the steam engine can provide the same horsepower as a 16 cylinder diesel. I'll tell you more about that later. But it is going to run at the same r/min as existing diesel and can be integrated into the existing diesel locomotive system. It does require a tender. The tender here houses the cold storage, the limestone storage, and baghouse for cleaning up the ash out of the flue gases. This tender is a passive unit. It's a closed cycle steam system which means the water is condensed and then used again and you have to carry a certain amount of makeup water on board. Now the modifications that would have to be done to the chassis are to move things slightly forward. That's the primary modification in terms of where the components are in the unit. Our philosophy was simply to allow the railroads to get the economic benefit of coal but in such a way that they could use the very cheapest coal. This Wormser is a great system and it can burn on the cheapest grades of coal. In fact they could burn the kind of coal that is normally thrown away today. And also recognizing that introducing coal is going to bring some change, we want to make the changes as minimal as possible. So we've built our system on the existing diesel locomotive. And to minimize development cost, there are two things. One is we use the prototype as a test platform using the alternator as a dynamometer. Second, our steam engine will be built on an existing diesel block which eliminates a whole area of development and therefore cuts down on development costs and time. We expect to have a prototype unit on the rails in 2 to 3 years. 2- to 3-year timeframe, there should be a prototype ready for testing.

Now the marketing outlook for a system like this one is to repower existing diesels. That doesn't mean you can just take an engine out of the roundhouse and drop this in. There have to be some modifications. But basically the electrical system could be as it stands or it could be upgraded to a more modern type that is available. A second option is that we could license our system to a major manufacturer. We don't see ourselves really as ever building brand new locomotives. But the system could be licensed or supplied to a major manufacturer for inclusion in a new locomotive. And a third option is that we could actually purchase a rebuilt chassis from a rebuilder. These locomotives are given a 12-month warranty. And put our own power plant into it.

OTHER APPLICATIONS

This system could easily be used in marine towboats or stationary generating plants or oil rigs. Anyplace a diesel in the 2,000 to 4,000 horsepower range is now used, this system could also be used.

The engine is based on modifying an existing diesel block. I won't go into all the details. But this shows an Electro Motor Division block. Basically the steam cylinders replace the cylinder heads on the diesel engine so that you have a steam system which is now on top of the diesel block. This is a twelve cylinder engine now providing 3,500 horsepower available for traction and the reason that can be done is simply that a steam engine is a much gentler engine than a diesel engine. Even because of the peak loads in the steam engine are less than the peak loads in the diesel. The crankcase has to be sized to take the largest load that the diesel engine can provide. However, on the average over the entire cycle that the engine operates you get more loads over the average, more force on the average, even when the peak loads are smaller. Therefore the crankcase will never see the highest loads that it sees in a diesel engine. This system is set up so that the original pistons that were in the diesel engine stay there but they now serve as crossheads. On top of the pistons are piston rods which go up to the steam cylinders. The steam cylinders are isolated from the crankcase so that in the initial design there are two lubrication systems. One for the crankcase which is the original diesel crankcase and also a steam system, a steam oil system, for the steam cylinders. However, there is a precedent for eliminating the use of oil in the steam by going to a special composite piston ring. So that you can actually eliminate the whole problem of lubricating the steam cylinders completely eventually—that's a long term development but its something we already are working on.

Now, this next set of slides has to do with the Wormser combustion system which is a brand new commercial fluidized bed system. Basically a fluidized bed is simply a vessel in which there is a perforated plate. On top of that plate sits sand or limestone or a material of that type. Combustion air is introduced through the bottom and it comes up through the perforations and it begins to make the sand bubble. In order to start the system, the combustion air is heated to on the order of 1,200 and crushed coal—not pulverized but crushed to a quarter by zero—is introduced into the system and it begins to burn. Heat here is of the temprature of combustion in a fluidized system is about 1,700 to 1,750 °F. This takes care of two major problems. First of all, its below the ash softening temperature of the coal so therefore, the ash goes off with the gases as a soft friable material. Second, its below the temperature at which most of the oxides of nitrogen are formed. So there's a major pollutant that you don't have to deal with. The elimination of the ash problem also eliminates the clinker problem that you do have in a standard stoker system.

Steam tubes are in the sand or they can also sit right on top of the sand and that is where the water is evaporated to make the steam. Basically, the real benefit here is the flexibility of the kind of fuel that can be used. You can burn slurries in it, you can burn run-of-mine coal, high sulfur, almost any type coal can be burned.

Senator WARNER. If I may interrupt. The old stoker really ran at a zero pressure and you're running at 1,200 psi?

Mr. PRAHL. No, this is the temperature. You start it at 1200 but it burns at 1700.

Senator WARNER. It burns at 1,700?

Mr. PRAHL. Yes and some of the systems are higher than that.

Senator WARNER. I'm trying to get some base point in my own mind as to this fluidized bed versus the old system.

Mr. PRAHL. Well, the situation with the fluidized bed is that you burn the coal by surrounding it with hot sand at a temperature of about 1,700 °F. Now that allows you to get pretty complete combustion without having to have the temperatures get up higher than that. Because you're surrounding the coal by hot sand rather than other coal coming in. So that's basically the principal. There is a diminished ash problem naturally, because the ash stays very soft. You collect it in a filter system. In the older systems, if the ash got to hot of course it would form clinkers. Clinkers are just—you know, the ash melts and forms a rock essentially. Less pollution.

Now this system also covers the sulfur problem. I have to show you the rest of the system before I can show you how that works. This is the Wormser Grate as adapted to an industrial situation. We also have adapted it to transportation situations. The secret here is that there are two shallow beds. The bottom bed is sand and the top bed is limestone. These beds are 6 to 8 inches in depth. Now that allows us another very attractive thing which is that because the beds are so shallow the total height of the system is small. It can be limited to something on the order of 9 feet which will fit on a locomotive easily.

In this industrial situation, about 60 percent of the steam is made here. The gases leave here at about 1,700 °F. and they go through the bed of limestone. This bed is at 1,500 °F. which is the optimal temperature for removing sulfur. So that all the gases pass through the limestone—the sulfur removal is very high—over 90 percent. The commercial systems that are operting now have better than 90 percent removal of sulfur. Its a direct coal-feed system and this would be the same on the locomotive. You store two by zero run-of-mine coal and its crushed and dried as its fed into the boiler. Gases leave here at 1,500 °F., they go through the wasteheat boiler. In the industrial situation, this is where 40 percent of the steam is made. In our situation, we use that heat for superheating steam. And then they leave this wasteheat boiler at 350 °F. and go to the baghouse. Limestone is fed in pneumatically as is the coal. The limestone resonance time is about 12 hours in the bed. It drains out almost like a bathtub and is collected in a disposal bin below, along with the ash. Basically, the features are its a dual bed system. That's the key, really, and direct coal feed.

This just summarizes, you have the separate beds. I think the thing that's of interest here is that the Wormser system uses steam tubes that sit up on top of the sand, not in the sand as is actually shown here. When the combustion air is on, there is splash that hits the tubes so this is the way that they use to control the response. By controlling the height of the splash and the amount of coal-feed they can actually follow loads almost instantaneously. In a single bed, they can do it on a 3-to-1 basis. The system can then follow loads in a similar manner to a locomotive, however, for the locomotive design we've changed the situation. And I'll show you a slide later, so that it can actually have a 12-to-1 turndown. That means you can instantaneously turn down to one-twelfth with a full load.

Again, you see by passing everying through the limestone you remove all the sulfur.

This is a commercial Wormser system in Amarillo, TX, IOB Processors and operating now since June and they use it for processing beef. This sytem is about twice the size that we put on a locomotive. You can already see that its relatively small.

This just is a size comparison to show you the Wormser system compared to other fluidized beds. There is quite a difference.

This is just summarizing what it can do.

OK, the 3-to-1 turndown. There are two ways to achieve it. One is by actually shunting material into a storage bed. This is what's done in the commercial system that's being used for processing right now. But in that system they've learned that if you don't mind fluctuations of about 100 degrees in the bed temperature, you don't have to remove material you can just control it by controlling the amount of combustion there in the coal. The system produces steam for our system at 1,000 degrees and 1,000 psi.

Basically, these are some of the benefits. You don't have a stone problem because the coal is directly crushed so therefore any stones that come in get crushed down to the fuel size essentially and they just add to the fluidized bed. No clinkers because you blow the ash. Melting temperature. And no slagging for the same reason. You don't have to recycle ash to pick up the extra carbon because whatever carbon escapes the first bed actually traverses through the limestone bed and is burned in that.

The big advantage here is that you can use the very cheapest coal available and can actually pick the lowest price that you want. Whoever can supply to you at the lowest cost can be used. Typically you can save $10 to $20 per ton, an operator could order the stoker-type coal, sized and graded for stoker use.

This is the system as it's been adapted. This is a preliminary design for the locomotive application. In this situation, all the steam is made in these steam tubes right here that sit right over the bed. Instead of a perforated plat, we have sparge tubes that are simply tubes that allow the combustion air to be fed out and to fluidize the bed. This removes the need for cleanup below here. In this situation, what we've done to get the twelve to one turndown is we've partitioned the bed into an area that's one-quarter and three-quarters. Now remember I said that each single area could have a three to one turndown. So if we turn this section off and then only use this section, we can turn this one down to three to one but we're only one-quarter of the area, since the firing rate is across the area of the bed which I think is about a twelve to one. It's one-fourth of one-third. So it's a twelve to one maximum turndown. As I said, all the steam is made here. In here is the superheater. This part is on the locomotive. The economizer is actually on the tender. The economizer really heats the feed water up.

That basically is the slide presentation and I'll be glad to answer any questions.

[The prepared statement of Mr. Prahl follows:]

NATIONAL STEAM PROPULSION CO.
225 MERRIMAC STREET WOBURN, MA 01801
617-938-9380

THE CE-635

A COAL-ELECTRIC LOCOMOTIVE

FOR

THE EIGHTIES AND BEYOND

ADVANCED DESIGN — PROVEN TECHNOLOGY

I. EXECUTIVE SUMMARY

It was the high cost of maintenance which finally ended the 120 year reign of the first steam locomotives on Class I railroads in America. Both coal and oil were cheap in the 1950's, but the diesel electric promised greatly reduced maintenance costs through standardization. By 1962 no major railroad operated steam locomotives.

In the 1980's and beyond, it is the high cost of oil as well as uncertain supplies which will bring the railroads back to coal as a fuel. A modern coal powered locomotive must be economical to operate and be compatible with railroad operating practices if it is to be acceptable.

The National Steam Propulsion Company (NSPC) has designed the CE-635, a coal burning locomotive using a steam-electric drive which offers the railroads a significant cost savings, even if oil prices drop somewhat from their present levels. The payback on the CE-635 is 2½ years with oil prices at $0.90 per gallon.

A fundamental aspect of the product design is that it is built on existing diesel-electric chassis. Only the combustion system and steam engine are new. This feature reduces development and production costs, but more importantly, it minimizes the changes required in railroad operations.

The steam engine is a 3500 horsepower unit built on an existing diesel block. Coal is fired in the Wormser Grate, a patented fluidized bed boiler capable of burning the cheapest run-of-mine high sulfur coal while meeting all present and anticipated air quality standards.

The CE-635 will be built on a remanufactured locomotive chassis or the power plant will be used to repower existing diesel locomotives presently owned by railroads. The NSPC power plant can also be supplied to or licensed to a major builder for incorporation into new locomotive chassis.

The CE-635 is a near term solution to the problem of high energy costs. A prototype unit will take about two years to construct.

II. INTRODUCTION

Railroads have been closely associated with coal since their inception in the early 1830's. The first steam locomotives burned coal although wood became the most common fuel until after the Civil War. By 1900 most railroads used coal as fuel. Railroads have both owned and hauled coal since the beginning. In fact, today, railroads transport more coal than any other commodity. So important was coal traffic to the Norfolk & Western and the Pennsylvania railroads that they resisted the growing pressure to dieselize in the 1950's for as long as economically possible, continuing to refine their steam locomotives. By 1962 no Class I line haul railroad operated coal fired lcomotives.

During the final years of the first steam locomotive era, there were three attempts to build steam-electric motive power. The Chesapeake & Ohio and the Norfolk & Western both built coal fired steam turbine electric locomotives. These units were very similar in concept and design: both were open cycle, although the C&O used a conventional fire tube boiler while the N&W employed a water tube boiler. The third attempt (some 15 years earlier than the other two) was a joint effort of the Union Pacific Railroad and the General Electric Company. This locomotive was designed to fire either bunker 6 fuel oil or pulverized coal. It was somewhat more advanced than the others, using a closed cycle as well as a water tube boiler. These attempts failed for the following reasons:

1. Costs were high - General Electric spent over $1,000,000 in 1938 with no end in sight.
2. There was no compelling reason to make them work since oil was cheap at the time, and the diesel promised reduced maintenance costs through standardization. C&O and N&W built steam-electrics primarily for political reasons.
3. There were a number of technical problems: complicated plumbing; freezing of the condensers in the case of the GE-UP locomotive; problems with the high pressure water tube boiler on the GE-UP unit; excessive firing rates and poor draft conditions on the C&O unit; poor turbine efficiency at partial loads; and finally both the C&O and the N&W locomotives had severe problems with fluctuating load conditions - when starting a heavy train, pressure dropped and performance lagged. All of these could have been solved if the incentive had been there.

The railroads changed from first generation steam locomotives to diesels in the 1950's primarily because of costly, labor intensive maintenance, not fuel costs. In the 1980's the high cost of oil has made coal attractive once again as a fuel for the railroad industry. Today a modern coal-burning locomotive will cost about 60 percent as much to operate as the diesel-electric annually.

In addition to its high cost, oil is subject to shortages and cutoffs. Any conflict in the Middle East, whether internal or part of a world wide disturbance, can critically reduce American oil supplies, even if America is not party to the conflict.

Another favorable aspect of coal burning locomotives is the fact that coal is an abundant, native resource. In effect, every BTU of coal burned represents one of imported oil saved. Coal is, therefore, politically as well as economically attractive to railway management; it is especially so when one considers that the coal producers are among the railroads' largest customers.

Clearly there is a growing market for a modern, practical coal-electric locomotive. The National Steam Propulsion Company (NSPC) has addressed this market with a coal-electric design based on applying advanced, yet proven steam engine and coal combustion technology to the existing diesel locomotive.

III. REQUIREMENTS FOR A MODERN COAL BURNING LOCOMOTIVE

The most important requirement of any new coal burning locomotive is that it be economical to operate compared to the existing diesel; it must have rapid financial payback. This means the locomotive must combine reasonable thermal efficiency with the ability to fire the cheapest grades of coal. It is to be expected that maintenance costs for a coal burning locomotive will be somewhat higher than for a diesel since there are two major systems rather than one. To be acceptable to the railroad industry, these increases must be kept to a minimum.

The second requirement of any new coal burning locomotive is that it be fully compatible with current railroad operating practice. Some of the specific conditions which must be met are as follows:

1. It must be capable of being MU'd* with similar units and with diesels:
2. Any new locomotive should be in the same power range as existing locomotives;
3. Maintenance procedures and sparing should be changed as little as possible;
4. Operation of a new coal powered locomotive must not require more labor than diesels and retraining of existing labor must be kept to a minimum;
5. It would be a significant advantage if the coal burning power plant could be used to repower existing diesel locomotives as well as in new locomotives.
6. The expense of installing wayside fuel depots must be minimized.

* Operated together with other locomotives under master control.

Finally, any new coal powered locomotive must be environmentally acceptable, capable of meeting existing and anticipated emissions standards. In fact, to be consistent with the economic requirement, a new coal burning locomotive should be able to burn run-of-mine coal, since this is the cheapest coal available (about half the cost of double screened, washed, coal).

IV. TECHNICAL DESCRIPTION

A. The System

The National Steam Propulsion Company (NSPC) is currently developing the CE-635, a coal-electric locomotive which uses an existing diesel chassis and components, essentially replacing the diesel power plant with a small-cylinder reciprocating steam engine and a coal-fired fluidized bed boiler. The system can be used to repower existing 6 axle locomotives of 3000 horsepower and greater. It can also be supplied to or licensed to a major builder for incorporation into new chassis. The design described herein is for a new CE-635 based on a modified SD 50 locomotive as manufactured by the Electro-Motive Division of General Motors (EMD). EMD is the major U.S. locomotive manufacturer with about 75% of the domestic market. The NSPC power plant is also applicable to the General Electric C-36-7 chassis with minor modifications.

National Steam retains most of the diesel electric unit, including the main and auxiliary alternators, traction motors, control system, and air brakes. The CE-635 requires a tender for fuel storage, and to house the filters which remove particulates from the exhaust gases. A layout of both the CE-635 locomotive and the tender is shown in Figure 1.

The CE-635 specifications are as follows. It will be a 3500 horsepower, 6 axle unit or equivalent, with a total weight of 382,000 pounds. The tender weighs 300,000 pounds, fully loaded. Locomotives in this power range have dominated the market since their introduction in 1981. The locomotive will be capable of burning run-of-mine, high or low sulfur coal, while meeting present and future emissions standards. This feature is due to the unique coal combustion system patented by Wormser Engineering, Inc. of Woburn, MA, which is the core of the NSPC locomotive.

In order to provide 3500 horsepower to the main alternator, the NSPC steam power plant will use 32,000 pounds of steam per hour. To produce this, the Wormser Grate will fire approximately 2 tons of coal an hour and use approximately 380 pounds of limestone per percent of sulfur in the coal. The overall power plant efficiency will be near 18%.

The selling price of a CE-635 based on a remanufactured locomotive chassis is expected to be $1,600,000 including the tender. The cost to a railroad for repowering one of their units will be $1,000,000.

B. The Steam Engine

The Steam Engine is a 12 cylinder reciprocating unit similar in arrangement to the existing diesel engine. Reciprocating engines have better efficiency than steam turbines over the speed range required in the locomotive application. The steam engine will have the same horsepower as the 16 cylinder engine it replaces. It will be a compound expansion unit using steam at 1000 deg F and 1000 psi in the high pressure cylinders and at 850 deg F and 180 psi in the low pressure cylinders.

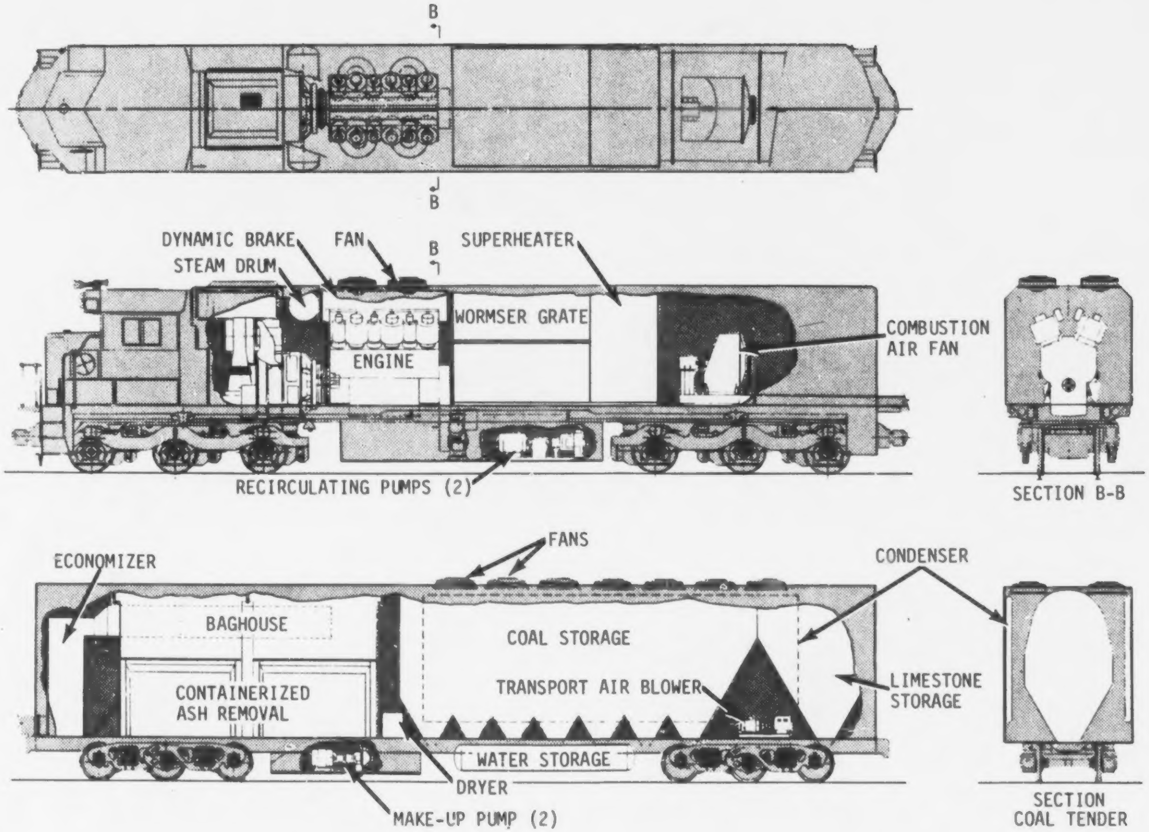

Figure 1. NSPC CE-635 Coal-Electric Locomotive

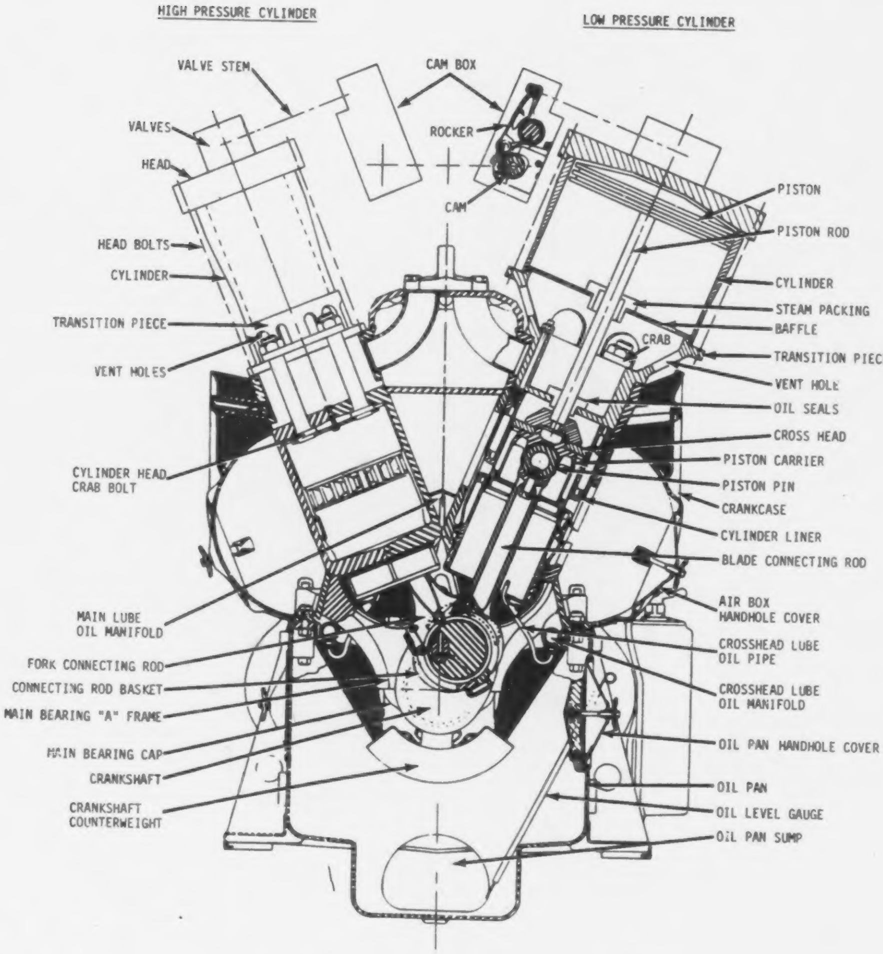

Figure 2. Cross Section Through Engine Block

The NSPC design is based on an existing diesel block, crankshaft, cylinders, pistons and piston rods. Also retained is the diesel camshaft drive. A cross section through the engine is shown in Figure 2. The figure shows an EMD block as the basis for the steam engine, but other blocks can be used. NSPC will fabricate steam cylinders, pistons and valves to fit the diesel block as shown in the figure. The steam piston rods are fastened directly to the diesel pistons which now serve as crossheads confining the side loads to the crankcase. The steam cylinders are isolated from the crankcase with gaskets and packing. Poppet valves driven by camshafts are employed. There are two separate lubrication systems. The crankcase is lubricated in the same way as the diesel engine except that the oil will not be contaminated by products of combustion and will therefore last longer. The steam cylinders are lubricated by injecting steam oil directly into the cylinders.

The CE-635 is fully condensing rejecting waste heat to the environment in order to recover process water. This means that the locomotive only has to carry make-up water on board to account for normal operating losses. The system will condense at slightly above atmospheric pressure, enabling simple venting of noncondensable gases, and eliminating the pumps, extra plumbing, and complexity associated with vacuum systems. Water will be returned to the hotwell (supply tank) by condenser steam pressure via a steam trap.

Condensing pressure will be controlled to within 1 or 2 psi by sequential operation of condenser fans and shutters. The fans will follow steam pressure and be sized to accommodate an extreme such as desert heat conditions. The shutters are intended to allow operation at below freezing ambients and will be controlled by condensate temperature; above freezing they will generally be wide open to minimize fan power.

C. The Steam Generator

Central to the NSPC design is the Wormser Grate two stage fluidized bed coal combustion system manufactured by Wormser Engineering of Woburn, MA. The Wormser Grate can burn the very cheapest grades of coal and produce 32,000 lb/hr of steam at 1000 deg F and 1000 psi while meeting all present and anticipated Federal and State air quality standards. Wormser Grate separates the chemistry of combustion from that of desulfurization by employing two shallow beds each less than a foot deep: a lower bed of sand and an upper bed of limestone. The upper bed is supported by a perforated plate through which the hot gas passes. Submersed in the lower bed are sparge tubes through which the combustion air passes. This is shown in Figure 3. The air has enough velocity to "fluidize" both beds causing them to resemble gently boiling porridge. The grate is started by preheating the combustion air until the sand reaches about 1200 deg F. Then coal is introduced pneumatically, and combustion begins. Coal is fired at 1700 deg F and combustion is nearly complete. Any unburned coal fines which might leave the combustion bed are burned in the limestone bed. This 1700 degree temperature is below that at which oxides of nitrogen are formed and below the ash fusion temperature. This means a major pollutant is eliminated immediately, and no clinkers are formed. Steam tubes pass directly over the bed in such a way that the hot sand is in contact with them when the combustion air is on.

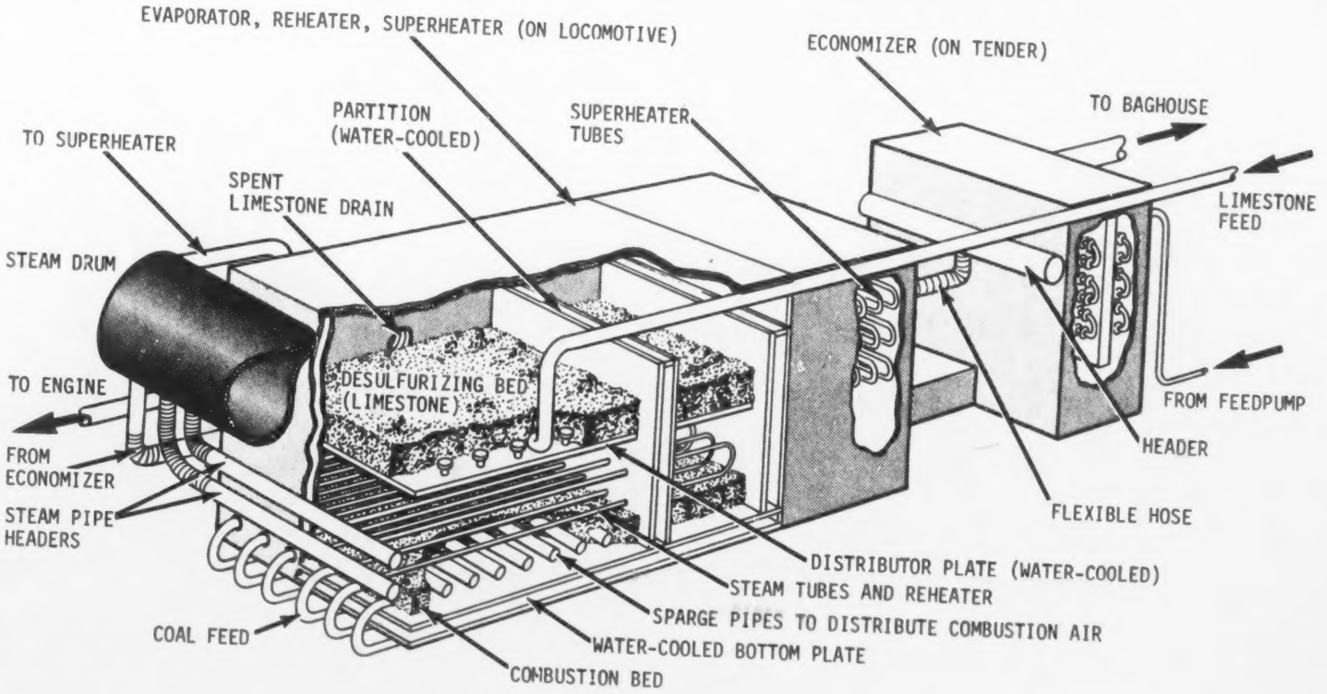

Figure 3. Wormser Grate Fluidized Bed Coal Combustion System

The hot gases leave the combustion bed and pass through the limestone bed. Because they must traverse the entire depth of this bed, the rate of sulfur removal is very high, about 99%. The sulfur dioxide in the combustion gases combines with the limestone forming calcium sulfate - ordinary gypsum. The spent limestone can actually be used to make concrete. The limestone is continuously replenished pneumatically. Spent limestone continuously drains from the bed and is carried to the tender. Of course, the Wormser Grate burns low sulfur coal even more efficiently than high sulfur coal. In this case no limestone is required; the upper bed is simply a second bed of sand in which the small percentage of coal fines escaping the lower bed is fired.

The gases leave the limestone bed at about 1550 deg F and pass into the waste heat boiler which contains the superheater. The gases exit the superheater and pass to the economizer which is on the tender. They leave the economizer and then go to the baghouse where the ash is removed.

By varying the combustion airflow and utilizing partitions in the beds a 12 to 1 continuously modulated turn-down can be achieved. This means that the CE-635 can follow changes in load in exactly the same manner as a conventional diesel-electric locomotive. The Wormser Grate is fully automatic and its control system will be integrated with the overall locomotive control system. The CE-635 operator controls will be practically identical to the existing diesel both in appearance and operation.

D. The Tender

The tender for the CE-635 is shown in Figure 1. It contains the baghouse for removing flyash from the exhaust gases, as well as 42 tons of crushed coal. Also on the tender is up to 12 tons of limestone and storage for the spent limestone. The tender houses the coal dryer, crusher, and the transport air blower. The tender will be supplied either as a passive unit or as a slug. A slug contains traction motors, but no prime mover. It draws power from the locomotive and is used to provide added tractive effort in starting heavy trains or on steep grades.

E. The Control System

The control system of the CE-635 must monitor and regulate more functions than on a diesel-electric locomotive. This is primarily due to the addition of a second major system, the boiler. On the coal-electric locomotive the analogue of controlling the amount of fuel into the diesel engine is regulating the steam throttle and the valve cutoff (the latter determines the mass of steam admitted to the cylinder during each cycle). In addition, the following boiler functions must also be controlled: 1) start-up, 2) combustion bed temperature, 3) combustion air flow, 4) coal feed rate, 5) steam drum pressure, modern microprocessor technology; all of these power plant functions will be regulated automatically. In addition, the NSPC power plant control system will be integrated with the existing diesel locomotive control system in such a way that the operator will find practically no difference either in appearance or operation between the coal-electric and the diesel-electric unit. The coal-electric will operate exactly like the existing diesel-electric with respect to MU control, braking (both dynamic and air), and wheel slip control.

V. SUPPORT REQUIREMENTS

Because the NSPC engine components are of the same scale as diesel components, engine maintenance procedures will change very little. Since the crankcase oil is cool and uncontaminated by operation, major engine overhauls are expected to be far less frequent than diesels. Periodic maintenance (crankcase oil changes) will also be reduced. Shops will have to add some equipment for boiler maintenance. Boiler maintenance will include regularly scheduled cleanout and replacing the steam tubes. The latter is expected to take place about every five years. Shop personnel will require some training in engine maintenance procedures, as well as instruction in boiler maintenance.

Some retraining of operating personnel will be required, but this is expected to be minimal. Engine crews should be made aware of the operating principle of the NSPC power plant, but aside from this, limited retraining will be needed since the overall operation of the locomotive will differ little from the existing diesel.

Wayside service depots will have bunkers for the storage of both coal and limestone. The bunkers will be weatherproof to prevent freezing in the winter. The tender bunkers will be filled using a conventional pneumatic transport system. 2" x 0 run-of-mine coal will be transported to the depots via hopper cars or trucks. The wayside service depots will include equipment for handling spent limestone as well as facilities for treating and storing makeup water.

VI. THE BOTTOM LINE

The CE-635 offers the railroads a significant economic advantage over the conventional diesel-electric as well as over the competing coal powered options. The reason for this is threefold: 1) the CE-635 can burn the very cheapest grades of coal - roughly half the cost of low sulfur, double screened, and washed coal, 2) the large overlap in parts between the NSPC unit and the existing diesel means minimal increase in maintenance costs and personnel retraining and 3) the purchase price is kept to reasonable levels through minimized development costs and extensive use of existing tooled components. In addition the CE-635 is a near term solution to the problem of high fuel costs. A prototype unit can be ready for testing in revunue service in two years.

Figure 4 presents a 15 year cost profile of the current diesel versus the CE-635. The costs shown are for one 3500 horsepower 6 axle, and are based on simple payback i.e., the time value of money is not considered, nor are any tax implications. The payback calculation assumes that the purchase price of CE-635 based on a completely remanufactured diesel chassis (an SD 40 or SD 45, for example) is $1,600,000. This price includes the tender as a passive unit, not a slug. The cost of a comparable new diesel locomotive (SD 50 or C36-7) was assumed to be about $1,200,000. The following table presents the assumptions about the annual operating costs per unit for each locomotive.

Annual Costs	Diesel	CE-635
Fuel	$ 384,000	$ 160,000
Limestone	—	14,000
Maintenance	55,000	80,000
Operating	13,000	16,000
TOTAL	$ 452,000	$ 270,000

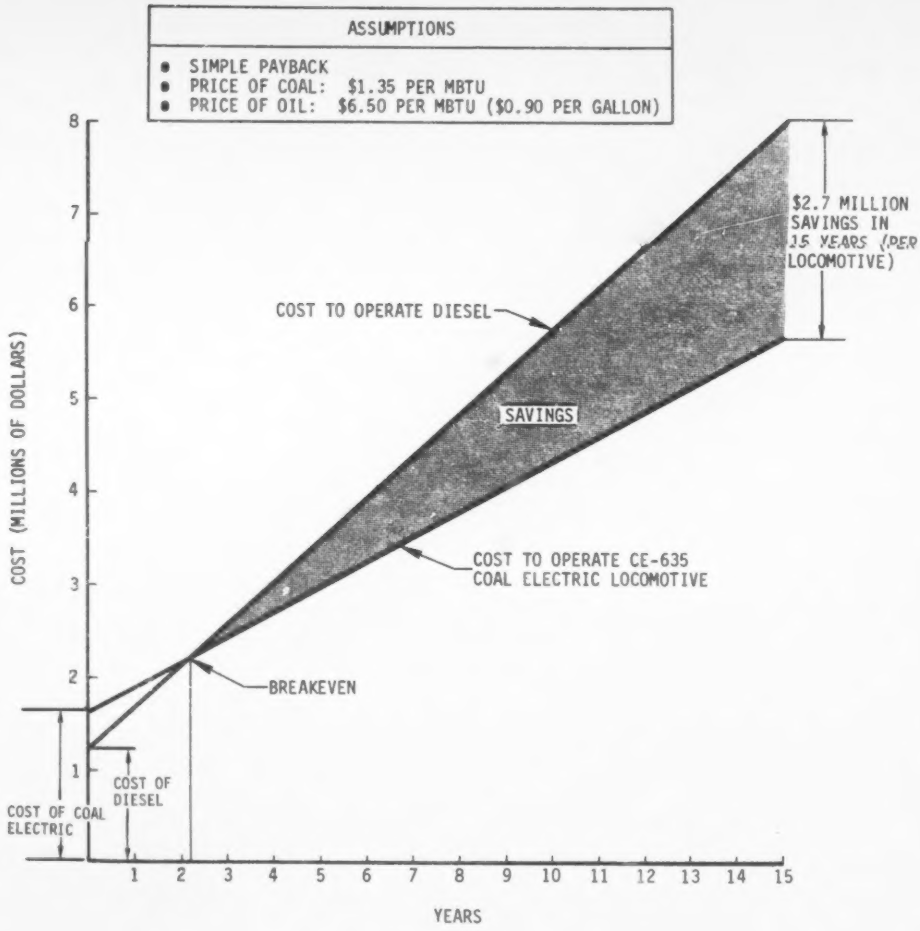

Figure 4. - Fifteen-Year Cost Profile: Diesel versus CE-635 Locomotive (Costs for One 3500-horsepower, six-axle locomotive)

Diesel fuel costs are essentially proportional to the cost per gallon since the heating value of diesel oil is relatively constant. The situation is not so simple for coal because of the wide range of costs per ton and the differences in heating values for different coals. These two variables can be combined by using the cost of coal per million Btu. In the above table the price of oil was assumed to be $0.90 per gallon or $6.50 per million Btu and the price of coal was taken as $1.35 per million Btu delivered. Fuel usage was estimated from the energy consumption of each type of locomotive: 59,000 million Btu per year for the diesel and 119,000 million Btu per year for the CE-635. The average limestone costs were approximated by assuming a coal with a heating value of 11,000 Btu per pound and a sulfur content of 3.5%. Maintenance and operating costs were taken from the Jet Propulsion Laboratory study entitled Future Fuels and Engines for Railroad Locomotives, performed for the U.S. Department of Energy and completed in November 1981.

With these assumptions the annual savings per locomotive is $182,000 and, as Figure 4 shows, the payback on the CE-635 is about 2.2 years. To get some idea of the impact this could have on a railroad, consider the following example. The Norfolk Southern Corporation owns about 2300 road haul diesels. Assume that due to depressed merchandise traffic in 1982, that 1300 locomotives were mothballed and that the remaining 1000 units were CE-635's rather than diesels. This would have saved NS approximately $182 million in 1982, increasing their total income before taxes by some 27 percent.

What's the bottom line? The CE-635 means increased earnings for the U.S. railroad industry as well as reliance on a native American resource.

VII. PROFILE OF THE NATIONAL STEAM PROPULSION COMPANY

NSPC was incorporated in November 1982 for the purpose of developing, manufacturing and marketing coal-fired power plants to the transportation industry, primarily the railroads and water transportation companies. It is a privately owned, closely held company. NSPC's business strategy is to work with a major corporation in the transportation field to demonstrate a prototype power plant in either a locomotive or in a towboat. It is expected that the corporation would make some financial commitment to the development of the prototype, but would not necessarily provide all of the required funds. The rest of the money would be raised through a tax-advantaged R & D limited partnership. In exchange for their financial participation, NSPC would negotiate an agreement with the corporation which could involve the exclusive marketing rights to the system, a licensing agreement possibly and equity position in NSPC.

NSPC was founded by three individuals and Wormser Engineering, Inc. of Woburn, Massachusetts. Company policy is established by the board of directors which include the founders among others. Brief biographical sketches appear below along with a profile of Wormser Engineering.

Frederick A. Prahl

Mr. Frederick A. Prahl is President of NSPC. He received his Bachelor's and Master's of Science in Mechanical Engineering from the Massachusetts Institute of Technology.

Mr. Prahl has over ten years of project management experience. He has directed contracts totalling millions of dollars, ranging from field measurement programs to paper studies and hardware development programs. As many as 20 engineers have worked under Mr. Prahl's direct supervision.

While at Foster-Miller, Inc., a Boston area mechanical engineering consulting firm, Mr. Prahl was responsible for the development of a complex system to inject an inorganic grout into roof bolt holes in coal mines for the U.S. Bureau of Mines. He has also managed a multidisciplinary program for the Department of Transportation to study the structural properties of railroad tracks. In particular, he planned and directed a massive field test program in which a controlled thermal buckling experiment was conducted on continuously welded railroad track. As part of this program he supervised the modification of two GP 38-2 locomotives so that their alternators could supply 7000 amps for the direct joule heating of the rails. This had never been done before and it was completely successful. Since the completion of these tests, the Southern Railway has used this technique to conduct their own buckling experiments.

Most recently, Mr. Prahl was a marketing manager for Foster-Miller, Inc. He engaged in both commercial and government marketing, including the management and production of more than a dozen proposals to the U.S. Government. His efforts resulted in over $1,000,000 of new business for the firm.

While at Foster-Miller, Inc., he has become professionally involved with the railroad industry, working with individual railroads, as well as government and institutions. He has valuable contacts in the railroad industry.

Henry H. Fuller

Mr. Henry H. Fuller is Vice President of Engineering. He holds bachelor's degrees from both Harvard and MIT, and a Master's from MIT.

Mr. Fuller is a leader in state-of-the-art steam engine technology. He has seventeen years of experience in thermodynamic engineering and steam engine design.

In his recent work at Foster-Miller, Inc., he was program manager and principal engineer on a solar powered steam engine project. The heart of this program was a high temperature, high efficiency steam engine, designed by Mr. Fuller. Mr. Fuller's other accomplishments at Foster-Miller include the design of a compact 60,000 lb/hr steam boiler, construction of a high temperature combustion chamber gas burner, and construction of a variable firing rate, residential gas burner. During his previous employment at Scientific Energy Systems, Mr. Fuller did system engineering for a steam powered coal haulage vehicle, and for a steam powered automobile. Mr. Fuller's primary contributions were the design, fabrication, and testing of the monotube steam generator, combustion system, and condensing system. Earlier, at Wingaersheek Turbine Company, he designed and tested high performance burners, and developed prototype plumbers' torches.

John P. Felleman

Mr. Felleman is Vice-President of Operations. Mr. Felleman holds a Bachelor of Science degree from MIT. During his employment at Foster-Miller, Mr. Felleman had responsibilities in marketing related areas such as proposal preparation and client presentations, in addition to his technical project work. While at Foster-Miller, Mr. Felleman designed and tested experimental coal mining machinery. He also developed specifications for and supervised the installation of a control and data acquisition system for a $3,000,000 experimental tunnel lining test facility. He participated in a test program to develop an axial load measurement technique for continuously welded rail.

Gordon B. Baty

Mr. Baty became president of Wormser Engineering in March, 1981, coming from Burroughs Corporation, where he was manager of Burroughs Imaging Systems Group, a part of the company's Office Automation Division. Prior to that he was a founder and president of Context Corporation, a manufacturer of optical character recognition systems for the word processing and computer industries, a firm which was acquired by Burroughs in 1979. Prior to that, Mr. Baty was a founder and president of Icon Corporation, a manufacturer of numerical control systems for industrial automation; that firm was acquired by USM Corporation in 1971. He has been an instructor for several years at Northeastern University, and has written extensively on business and technical topics. Mr. Baty holds B.S., M.S. and Ph.D. degrees from MIT's Sloan School of Management.

Lawrence A. Goldmuntz

Dr. Goldmuntz is President of Economics & Science Planning, Inc., a Washington, D.C. consulting firm specializing in studies relating to Federal energy, transportation and research policies. He is Chairman of the National Academy of Science's Evaluation Panel for the National Engineering Laboratory of the National Bureau of Standards, and is also Visiting Professor of Engineering and Public Policy at Carnegie-Mellon University. Dr. Goldmuntz has served on many other federal scientific advisory councils and task forces. He was founder of TRG, Inc., a manufacturer of defense communications, navigation and countermeasures systems, later sold to Control Data Corporation, where Dr. Goldmuntz served as Division General Manager. He holds B.E.E., M.E.E. and Ph.D. degrees from Yale University, and resides in Washington, D.C.

Wormser Engineering

Wormser Engineering, Inc. is a manufacturing and engineering company dedicated to the design and production of clean and economical systems for the direct use of coal. The firm was founded by Alex F. Wormser in 1974, in response to the severe oil price shocks felt throughout the West at that time. The company is committed to the concept that coal, being the world's most abundant fossil fuel, must play a major role as an energy source in the next several decades, and that the combustion represents the most economic way for it to be used on a wide scale in the near future.

The Company has developed and patented a unique new technology utilizing multiple fluidized beds for the combustion of coal. This technology is usable for generation of industrial process steam as well as for hot air generation, and in electrical cogeneration systems. Certain of the Company's products are manufactured and marketed by the Company; others are being made available for licensing for specific markets. Wormser is believed to be the only company in the United States dedicated exclusively to fluidized bed coal combustion technology.

The Company has been quoting Wormser Grate FBC systems with full commercial guarantees since January 1981. Initial contracts for full scale commercial systems were received in 1981.

Corporate and engineering offices, as well as production facilities are maintained in Woburn, Massachusetts. A research and development facility is maintained in Beverly, Massachusetts.

Wormser Engineering is privately owned by individual investors, a group of financial institutions, and by the employees.

Senator **Warner**. I note that it appears that your company has had the courage to go out on its own with no Federal funding in this?

Mr. **Prahl**. No, we have some private funding at the moment. We think a prototype will cost $6 to $7 million and take 2½ to 3 years.

Senator **Warner**. And that's an operating prototype?

Mr. **Prahl**. Yes. Not a production model but this would be something we can operate. It could be tested.

Senator **Warner**. We have heard from the two principal manufacturers of diesel locomotives today. Where are you in this framework between the users and the manufacturers? Are you prepared to enter into competition with two giants?

Mr. **Prahl**. I don't think we ever thought we would be entering into competition with either of those companies.

Senator **Warner**. Are they taking a look at that over your shoulder, with your permission?

Mr. **Prahl**. Yes, we have talked to both companies, one company extensively. They know exactly what we're doing.

Senator **Warner**. And they've expressed an interest?

Mr. **Prahl**. They're interested. I think they may feel its too risky at the moment to do something about. Our feeling is we'll work very hard to get a prototype built because we believe it can be done. And we'll do it through private funding. With Government help, if you will.

Senator **Warner**. Very encouraging, I thank you.

What's your thought of how we should structure a Federal program to perhaps get into the prototype business? Perhaps both you and Mr. Thomas could supplement the record upon further reflection and perhaps further consultation with your colleague as to how a Federal subsidy program might be structured.

Mr. **Prahl**. My thoughts are very similar. We are intending to structure an R&D partnership development and I don't see any reason why the Government couldn't participate in that. We never assumed that the Government would pick up the entire cost of a prototype development program. We are trying to develop a joint venture with a major industry to give us some credibility to sell the R&D partnership essentially. We are talking to a major investment banking firm about what it would take to make this credible and certainly Government participation would be welcome. And it doesn't have to be all of the participation. Our program, we think, is a research and development program. I might point out, I didn't say this before but our vice president of engineering has had a great deal of experience in developing high-temperature, high-pressure steam engines. He did a project which wass for the EPA in developing a steam car. It was actually a project for emissions not for alternative energy but they took a Dodge Monaco and modified it to steam at 1,000 degrees and 1,000 psi. A four-cylinder steam engine that met all of the regulations, all of the original 75 emissions regulations, and it ran on a dynamometer for 5,000 miles. Chrysler supplied the unit. That was an enormous undertaking. That's basically what I think—its participation with the private sector.

Senator **Warner**. All right, sir. Would you kindly provide for the record any supplemental thoughts that you might have on it. How a couple of programs may be structured.

Mr. **Prahl**. I'd be glad to.

STATEMENT OF KENNETH M. THOMAS, PRESIDENT, BROBECK CORP., BERKELEY, CA

Mr. **Thomas**. I'm going to make a few comments on the reintroduction of coal fuel for railroad locomotives. Brobeck Corp. was founded over 25 years ago by Bill Brobeck who was one of the chief engineers at the Lawrence Berkeley Laboratory. Since that time, the company has played a major role in many of the nuclear particle accelerators built around the United States and some international projects. Most recently we completed the cost estimate for a staffing study and the schedule for the National Electronic Accelerator Laboratory, which you were so instrumental in bringing to Virginia. During the last 10 years, we have also been responsible for the spinoff of four other small companies. During this same period, we also began to play an increasing role in transportation technology. Early in the period the company, under contract with the California Department of Transportation, designed, fabricated, and tested the steam engine as a replacement for a conventional diesel engine in the transit bus. And we have a hybrid gasoline automobile and an auxiliary power unit to provide emergency propulsion power to electric trolley buses in operation in Berkeley. This earlier experience with the steam and the recognition that our petroleum-based transportation system had become very vulnerable to foreign control led us to begin to explore alternative fuels for railroad locomotives. The interests of the hour today—I won't repeat all the good reasons that have been outlined before me for using coal as a fuel for locomotives.

Senator **Warner**. Well now, they're parallel to what's been expressed today by myself and other members?

Mr. **Thomas**. Very parallel, that's correct. Updating the design of the steam locomotive is obviously one approach to burning raw coal in locomotives. And I'm defining raw coal as Fred did, a few minutes ago, its essentially largely unprocessed. It certainly hasn't reached the slurry state. And I'm using that as the raw coal consideration. You will also hear in a few minutes about another approach to steam locomotives. The results we believe, should be examined to evaluate the practicality of steam in today's environment. Our experience with steam in automobile, city bus, and railroad service suggest that the best alternative is to generate gas from the raw coal and burn the gas in an engine or turbine which drives the locomotive through the conventional electric transmission system.

The gasified coal system consists of a locomotive with a gas burning engine and a producer car. The gas producers are essentially circular tanks in which the coal is burned together with the coal supply and the gas cleaning equipment are carried on the producer car following the locomotive. The locomotive itself carries the prime mover—the gas engine—and the conventional electric transmission.

Our study suggests that by gasifying coal and burning the resultant gas in a reciprocating turbine engine, a somewhat higher overall efficiency can be achieved than is possible with steam. More importantly, however, we believe the existing locomotive fleet can be converted thereby reducing the fleet conversion costs. Further, raw coal can be burned and the attractive features of the electric propulsion system can be retained. The range and the power of the locomotive will be comparable to existing locomotives.

Both the engine and combustion equipment will be microprocessor controlled in order to take advantage of the flexibility and economy offered by this modern technology. Generation of gas from coal is an old art which was in common use until supplanted by natural gas after World War II. In the last few years, engineering development of coal gasification has been carried forward in response to potential oil and gas shortages. Producer gas powered road vehicles diring both World Wars, especially in contries where liquid fuels were not available. These installations operated automatically and illustrated the wide range of sizes in which gas producers can be had. The object of our project is to build on this prior art, adopt it to railroad use and improve it through the use of new materials and techniques where they apply. We believe the potential problems with mobile application lend themselves to straightforward engineering solutions and no state-of-the-art research is required. The same technology, by the way, is appropriate to an even greater market, namely, marine engines.

The most difficult and critical next step in our project is arranging financing for a program to develop a commercial prototype. We have in mind some static systems, tests followed by an engineering prototype, production prototype, and finally a commercial prototype.

Completion of a locomotive system which any locomotive operator can take across country without theneed for supporting scientists and/or engineers is critical to the acceptance of a coal-burning locomotive by the Nation's railroads. In spite of all the benefits to the railroads and society, financing the program is not likely to be easy. The railroads tend to be extremely conservative, placing a high dependence on reliability. This aversion to risk taking causes the railroads to be especially reluctant to join with smaller innovative companies in solving technical problems. At the same time, there is little incentive for the major locomotive manufacturers to introduce coal-burning locomotives. They both have proven designs and heavy investment in production tooling for their existing diesel locomotives. I'm certain that they can't get very excited about spending large amounts of precious development money when the major benefit more than likely with the inflation of sales of existing units and the sales of coal-burning locomotives as opposed to sharply increased overall sales. I don't mean either of those remarks about the railroads that are locomotive manufacturing companies in any critical way. I am sure if I were involved in their companies and looking for bottom-line performance, I would make the same kinds of judgments. I think it's an example of the kind of inertia and motivation that perhaps some other mechanisms might provide aid.

We firmly believe that because of the large economic advantages to the railroads and improved security of our Nation, the inertia of railroads and the lack of motivation by the major manufacturers can ultimately be overcome.

In conclusion, may I suggest that in the conversion of our locomotive fleet from diesel to coal burning we have an opportunity to revitalize our locomotive fleet and to free our railroads from their dependence on foreign oil and by effectively joining the interests and needs of the public sector with those of the private sector we can accelerate this conversion.

[The prepared statement of Mr. Thomas follows:]

REINTRODUCTION OF COAL AS FUEL
FOR RAILROAD LOCOMOTIVE

SENATE COMMITTEE ON ENERGY & MINERAL RESOURCES
Chairman - Senator John W. Warner
November 28, 1983

SUMMARY OF ORAL COMMENTS BY
Kenneth M. Thomas, President
Brobeck Corporation

FIELD HEARING
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210 Franklin Road, S.W.
Roanoke, Virginia

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Thank you for permitting me to make a few comments on the Reintroduction of Coal as a Fuel for Railroad Locomotives.

Perhaps just a few background comments might be helpful. Brobeck Corporation was founded about 25 years ago by William M. Brobeck, then Chief Engineer of the Lawrence Berkeley Laboratory. Since then, the company has played a key technical role in many of the nuclear particle accelerators built in the United States.

Most recently, we completed the cost estimate, staffing plan and project schedule for the National Electron Accelerator Laboratory which you, Senator, were so instrumental in bringing to Virginia.

During the last ten years, the company has been responsible for the spin-off of four other companies.

During this same period, we also began to play an increasing role in transportation technology. Early in the period, the company, under a contract with the California Department of Transportation, designed, fabricated and tested a steam engine as a replacement for a conventional diesel engine in a transit bus. Currently, we have a hybrid, electric/gasoline, automobile and an auxiliary power unit to provide emergency propulsion power for electric trolley buses in operation.

It was this earlier experience with steam and the recognition that our petroleum based transportation system had become very vulnerable to foreign control that led us to begin to explore alternative fuels for railroad locomotives. Our analysis agreed with many experts in the field that petroleum will gradually rise in price as the oil supply becomes exhausted and that this price rise, while subject to fluctuations, will become even more oppressive within the lifetime of locomotives now being manufactured. Coal, on the other hand, is plentiful in our country with a reserve estimated at more than 100 years at the present rate of consumption. It's present cost for comparable energy is one half that of diesel fuel.

Thus, the widespread use of coal in railroad operations can reduce the railroad's fuel bill from about $4 billion to about $2.0 billion dollars per year. Further, many railroads haul large quantities of coal and, thus, have it readily available. It has been estimated that the resultant increase in coal utilization would provide 15 to 20 thousand additional jobs in the coal industry.

But--perhaps even more significant when one considers the current international conflicts threatening our petroleum supply, the use of coal on our nation's railroads will free this vital transportation link from its dependence on a foreign fuel supply.

Just last month, former Energy Chief James Schlessinger warned that we are far more vulnerable today than we were in 1973. Further, that "by the early 1990's, our own production of crude oil will have fallen by a million to a million and a half barrels per day. We will probably be down to about 7 million barrels a day and imports will have risen again to perhaps 45 to 50 percent of our total oil consumption."

Updating the design of the steam locomotive is obviously one approach to burning raw coal in a locomotive. Others are pursuing this approach and their results should be examined to evaluate the practicality of steam in today's environment. Our experience with steam in automobile, city bus, and railroad service suggests the best alternative is to generate gas from the raw coal and burn the gas in an engine or turbine which drives the locomotive through the conventional electrical transmission system.

The gassified-coal system consists of a locomotive with a gas-burning engine and a producer car. The gas producers, which are essentially circular tanks in which the coal is burned, together with the coal supply and the gas cleaning equipment are carried in the producer car following the locomotive. The locomotive, itself, carries the prime mover, the gas engine, and the conventional electrical transmission which drives the wheels.

Our study suggests that by gassifying the coal and burning the resultant gas in a reciprocating or turbine engine, a somewhat higher overall efficiency can be achieved than is possible with steam. More importantly, however, the existing locomotive fleet can be converted, thereby reducing the fleet conversion cost. Further, raw coal can be burned and the attractive features of the electric propulsion system can be retained. The range and power of the locomotive will be comparable to existing locomotives. Both the engine and combustion equipment will be microprocessor-controlled in order to take advantage of the flexibility and economy offered by this modern technology.

Generation of gas from coal is an old art which was in common use until supplanted by low-cost natural gas after World War II. In the last few years, engineering development of coal gassification has been carried forward in response to potential oil and gas shortages. Producer gas-powered road vehicles were used during both world wars, especially in countries where liquid fuels were not available. These installations operated automatically and illustrated the wide range of sizes in which gas producers can be built.

The object of our project is to build on this prior art, adapt it to railroad use, and improve it through the use of new materials and techniques where these apply. We believe the potential problems with mobile applications lend themselves to straightforward engineering solutions and that no "state of the art" research is required.

The same technology, by the way, is appropriate to an even greater market -- marine engines.

The most difficult and critical next step in our project is arranging financing for a program to develop a commercial prototype.

We have in mind some tests of static system elements followed by an engineering prototype, a production prototype and, finally, a commercial prototype. The completion of a locomotive system which any locomotive operator can take across country without the need for supporting scientists and/or engineers is critical to the acceptance of a coal-burning locomotive by the nation's railroads.

In spite of the benefits to the railroads and to society, the financing of the program is not likely to be easy. The railroads tend to be extremely conservative placing a high dependence on reliability. This aversion to risk-taking causes the railroads to be especially reluctant to join with small but innovative companies in solving technical problems. At the same time, there is little incentive for the major locomotive manufacturers to introduce coal-burning locomotives. They both have proven designs and heavy investment in production tooling for their existing diesel locomotives. I am certain they can't get very excited about spending large amounts of precious development money when the major benefit more than likely will be the replacement of sales of existing units with sales of new coal-burning locomotives as opposed to sharply increased overall sales.

I don't make either of these comments critically. Were I responsible for bottom-line performance in the respective companies, I might well take the same approach to major new development projects.

We firmly believe that, because of the large economic advantages to the railroads and the improved security to our nation, the inertia of the railroads and the lack of motivation by the major manufacturers will ultimately be overcome.

However, when one contemplates the delicate nature of our petroleum supply and the multi-year development period for a commercial prototype of a coal-burning locomotive, there appear to be powerful reasons for the Federal government to make a positive effort to encourage conversion.

In conclusion, may I suggest that, in the conversion of our locomotive fleet from diesel to coal-burning, we have an opportunity to revitalize our locomotive fleet and to free our railroads from their dependence on foreign oil. By effectively joining the interests and needs of the public sector with those of the private sector, we can accelerate this conversion.

Thank you, again.

ANSWERS TO SENATOR WARNER'S QUESTIONS

1. Mr. Thomas, you have very tactfully dealt with two problems, the inertia of the railroads and the lack of motivation by the major manufacturers, which I believe, may be fundamental to the problem of conversion.

   Has your firm been in contact with the major producers of locomotives in the U.S.?

   > Only superficially. Actually, our project will not be ready for responsible discussions until after the first of the year.

2. How do you believe the Federal government can encourage the coal conversion of our locomotives?

   > Although we do not believe that the Federal government should attempt to design a coal-burning locomotive as it did a new transit bus a few years ago, it might:
   >
   > 2.1 Clarify the energy tax credit rules to assure that tax credits are available in applications where petroleum is replaced by coal whether or not there is a net energy savings.
   >
   > 2.2 Enter directly into R&D partnerships as the funding partner to develop commercial prototypes of coal-burning locomotives perhaps retaining financial rights which would assure repayment of the development expense as coal-burning locomotives are put into service.
   >
   > 2.3 Provide direct tax incentives to railroads to encourage them not only to make this conversion but to generally upgrade their facilities to take advantage of modern technology.

3. Mr. Thomas, will you please forward the expert information on the clarification of the energy tax credits as soon as you have it?

   > Yes sir.

4. If the Federal government chose to stimulate the conversion to coal-burning locomotives by funding one or more prototype locomotives, what, in your opinion, would be the cost?

   > Based on the prior testimony by the representative of National Steam Propulsion Company and the testimony you will hear next, it would appear that the "per project" cost is in the $7M to $45M range. Thus, if three projects are to be funded, the total cost is in the order of $100M to $150M. I feel strongly, Senator, that the goal of the project should be a commercial prototype with milestones at which the project will be measured and allowed to proceed or be cancelled. I am completely opposed to small study projects, one following the other. I believe that if the earlier, broader goal approach is taken, that a commercial prototype can be operating in plus or minus four years.

5. When you have had a chance to discuss this hearing with your colleagues, please suggest a means by which Federal government might help with financing.

   > Yes sir.

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THE GASIFIED-COAL LOCOMOTIVE

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ABSTRACT

A concept is outlined for a coal-fired railroad locomotive. The objective is to reduce operating costs and to capitalize on the availability and abundance of a domestic fuel resource. The use of available and proven technology is emphasized. Design features include the use of on-board gas producers to fuel a spark-ignited reciprocating gas engine. A gas turbine could also be used. Electric drive, already familiar and reliable, is retained. Efficiency, costs and environmental protection are discussed.

The cost saving and assurance against supply interruption makes the return to coal as a locomotive fuel a possibility that merits careful consideration. The use of coal energy with several alternative engines is being studied and discussed at this time. Coal may be converted to other forms of fuel or it may be burned directly; both internal and external combustion engines have been tried or proposed (1,3). Among the possible coal-fired systems is conversion of the coal to gas and the generation of the power by a gas-burning internal combustion engine or turbine. The purpose of this paper is to discuss the features of such a system and to present a conceptual design of what is here called a gasified-coal locomotive.

TYPES OF GAS PRODUCIBLE FROM COAL

Generation of gas from coal is an old art which was in common use until supplanted by low-cost natural gas after World War II. In the last few years, engineering development of coal gasification has been carried forward in response to potential oil and gas shortages (4). Reference 5 is cited to indicate the maturity and availability of knowledge in gas producer technology.

Several different processes producing gas of different properties have been widely used. These processes have generally been distinguished by the heat content of the gas. Table 1 lists the typical types of gas made from coal or coke and their heating values. In most cases, a major constituent of the gas is carbon monoxide, usually with hydrogen produced from steam introduced with the combustion air.

TABLE I. TYPES OF GAS MADE FROM COAL

TYPE OF GAS	TYPICAL HEATING VALUE MEGAJOULES PER CUBIC METER (BTU PER CUBIC FOOT)	SOURCE
Blast furnace gas	3.7 (100)	Blast Furnace
Producer gas	5.6 (150)	Reaction of carbon with air and steam
Water gas, blue gas	11.2 (300)	Reaction of carbon with steam
Carbureted water gas	18.6 (500)	Water gas plus hydrocarbons
Illuminating gas, city gas, coal gas	18.6 (500)	Destructive distillation of coal
Synthetic natural gas	33.5 (900)	Hydrogenation of coal - Reaction with oxygen and steam

The term "coal gas" is also used to distinguish natural gas from gas made from coal.

When the gas is to be stored or transmitted long distances, heating value is important because it determines the storage and pipe-line costs. However, when the gas is used where it is made, as on a locomotive, heating value per cubic foot is of little concern. Because of the continuous operation, complete consumption of carbon, simplicity and efficiency of the gas producer, producer gas appears the best choice for the locomotive application.

GAS PRODUCERS

Gas producers consist of a tank, usually cylindrical with its axis vertical, in which a bed of coal a few feet thick is maintained (5). Air and steam pass through the coal and are converted to fuel gas by the reactions with carbon listed in Table 2, and with other constituents of the coal. The carbon reactions, which are the most important, occur in two stages. In the incandescent zone, the reaction described by Eq. (1) proceeds. Further through the coal bed, where the temperature is lower, the carbon dioxide is reduced according to Eq. (2), producing the carbon monoxide which is the principal source of the heating value of the gas. The overall effect of the two reactions is described by Eq. (3).

TABLE 2. REACTIONS IN PRODUCER GAS PRODUCTION

1. $C + O_2 \rightarrow CO_2 + 395\ 000$ joules (94 300 calories)[1]
2. $CO_2 + C \rightarrow 2CO - 171\ 500$ joules (41 000 calories)
3. $C + \frac{1}{2}O_2 \rightarrow CO + 111\ 500$ joules (26 650 calories)
4. $CO + \frac{1}{2}O_2 \rightarrow CO_2 + 283\ 000$ joules (67 650 calories)
5. $C + H_2O \rightarrow CO + H_2 - 130\ 100$ joules (31 100 cal.)
6. $H_2 + \frac{1}{2}O_2 \rightarrow H_2O + 242\ 000$ joules (57 850 calories)

Of the 395 000 joules per gram mol available from the complete combustion of carbon according to Eq. (1), 111 600 joules are released in the gas producer according to Eq. (3). The remaining 283 000 joules available from the combustion of the carbon monoxide according to Eq. (4), which is 75% of the heat available from complete combustion of carbon, remains in the gas. The carbon also reacts with steam according to Eq. (5). Practically all of the heating value of this carbon is available in the gas through the subsequent combustion of the hydrogen according to Eq. (6). In the gas producer, three of the reactions, Eq. (1), (2) and (5), proceed at various rates at various places in the coal bed and their products combine with those of the other constituents of the coal. The net result is that as much as 80% of the heating value of the coal remains as heat of combustion of the gas.

In spite of the apparent complication of the process, the reactions are effectively self-regulating. The flow of air is controlled by the demand for gas. Steam flow is set to hold the temperature below the ash fusion point where clinkers would form. As long as the coal level is maintained, the steam-to-air ratio, as observed by the temperature of the mixture, is kept constant, the ash is removed and the coal bed is gently stirred, the gas production takes care of itself.

The performance of gas producers is well described in References (5) and (12). The production rate and heating value of the gas depend on the air flow rate and the steam content of the air. For example, tests reported on Pg. 34 of Ref (5) showed a gasification rate of 155 kilograms of coal and 572 cubic meters of gas of 6.32 megajoules per cubic meter, per square meter of producer cross section per hour. (Gas measured at ^{0}C and atmospheric pressure). At this operating point, 76% of the heating value of the coal remained as heat of combustion of the gas. The steam consumption was 20% by weight of the coal gasified.

GAS ENGINES

A principal use of producer gas was to supply internal combustion engines before petroleum-based fuels became generally available. Since World War II, such gas-engine power generation has practically disappeared, except in connection with blast furnaces, due to the availability of oil and natural gas. Gas engines had very good thermal efficiences, close to 30%, but fall short of diesels in that respect (6,7). From reported test results on producer plants, an overall thermal efficiency from the coal to the engine crankshaft of 20 to 25 percent can be expected. Similar efficiencies should be achievable with a turbine as the prime mover.

THE LOCOMOTIVE SYSTEM

The concept of the gasified-coal locomotive thus becomes clear. The coal is gasified by a group of gas producers carried in a tender or producer car. Gas is cooled and cleaned in the producer car and piped to the engine or turbine with conventional electric drive to the wheels. The gas producers themselves, as illustrated in Fig. 1, are tanks containing a bed of coal about one meter deep. An updraft producer is shown with air mixed with steam introduced through a central grate at the bottom. The moist air is drawn through the producer by suction. Coal is fed and the gas taken off above the bed. Ash is removed through the rotating grate. To maintain uniform temperature and gas generation across the horizontal sections of the bed, a rotating rake is driven from the top head and the air inlet, which is located eccentrically, rotates with the grate. These features are typical of the later designs of stationary gas producers.

Table 3 gives the principal dimensions and quantities of the conceptual design. To generate 2238 kilowatts (3000 horsepower) in an engine of 30% efficiency requires 26.9 billion joules per hour. With a "cold gas" efficiency of 70%, coal of 27.9 million joules per kilogram, and a gasification rate of 146 kilograms of coal per square meter per hour, the producer area required is 9.40 square meters, or four producers of 1.83 meters diameter. Because the heating value per cubic meter of mixture entering the engine cylinders is lower than that of a hydrocarbon-fueled engine, the product of RPM, displacement and supercharging pressure must be considerably increased over that of a conventional engine.

Reference (12).

[1] This heat of combustion is for carbon as graphite. An average value for carbon as coke is 406 000 joules (97 000 calories) per gram mol.

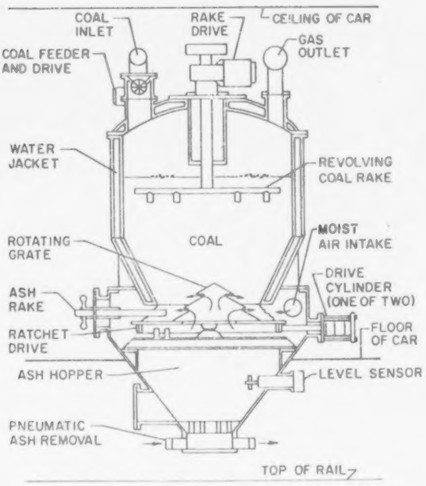

FIGURE 1. Gas Producer Elements

The gas is cleaned in several stages. Tar and dust must be removed to prevent trouble in the engine and sulfur should be removed both for the sake of the engine and to minimize air pollution. The gas first passes through a cyclone separator to remove dust and is then cooled and washed by water cooled in overhead radiators. A second washing circuit removes sulfur which is almost entirely in the form of hydrogen sulfide. Wash water and solvents are reclaimed and the accumulated waste products are stored in tanks under the car to be disposed of at the ends of the runs.

Auxiliary power required by the producer system is not large. The rotating speed of the coal-stirring rakes and grates of the producers is only a few revolutions per hour. The air flow is produced by the engine supercharger which is driven by engine exhaust gas. Cooling water pumps all of which operate at low pressures and radiator fans are the principal auxiliary loads. The possibility exists of generating auxiliary power from the sensible heat of the hot gas leaving the producers which must, in any case, be cooled.

CONTROL

Control of the producer system can be made entirely automatic with sensors for all of the important quantities and modern computer logic. The producer car would be unoccupied in operation. The driver would have the same controls as presently used on a diesel-electric locomotive.

TABLE 3. GASIFIED COAL LOCOMOTIVE CHARACTERISTICS

Maximum continuous power	2238 kw (3000 hp)
Engine displacement	400 liters (24 430 cubic inches)
Number of cylinders	18
Bore and stroke	.30 x .30 m (12 x 12 inches)
Piston speed	610 m/min (2000 ft/minute)
Rotating speed	1000 RPM
Boost pressure	52 kPa (1/2 atmosphere)
Drive	Electric
Gas producer type	Updraft-suction
Number	4
Diameter	1.83 m (6 feet)
Firing rate	146 kg/hr m^2 (30 lbs. coal/hr ft^2)
Coal consumption at full load	1540 kg/hr (3400 lbs/hr)
Coal bunker capacity	24 500 kg (54 000 lbs.)
Producer car length	19.8 m (65 feet)
Water tank capacity (on locomotive)	12 100 liters (3200 gallons)

Fig. 2 is a conceptual layout of the producer car. Fig. 3 is a schematic flow diagram. Coal to provide the same travel distance as a comparable diesel locomotive is carried in a bunker on the car and distributed to the gas producers by pneumatic conveyor. Ash from the producers is returned by vacuum conveyor to the ash bunker.

Air is drawn through the producers by a turbocharger on the locomotive. Because carbon monoxide is toxic, it is desirable to operate the gas piping below atmospheric pressure. Steam is generated from water heated at low pressure in water jackets on the producers. Water for generating the steam is carried in tanks on the locomotive which replace those used for diesel fuel.

The ability of the gas producers to follow load changes has been demonstrated in automobile use which was widespread in Europe during World War II (8,9). Some time, probably half an hour, must be allowed for starting and some gas will probably have to be flared during this period.

THE PRIME MOVER

Producer gas can be burned in reciprocating engines or turbines. Although there appears to be no use of producer gas today, gas engine technology was, at one time, well-developed for stationary applications.

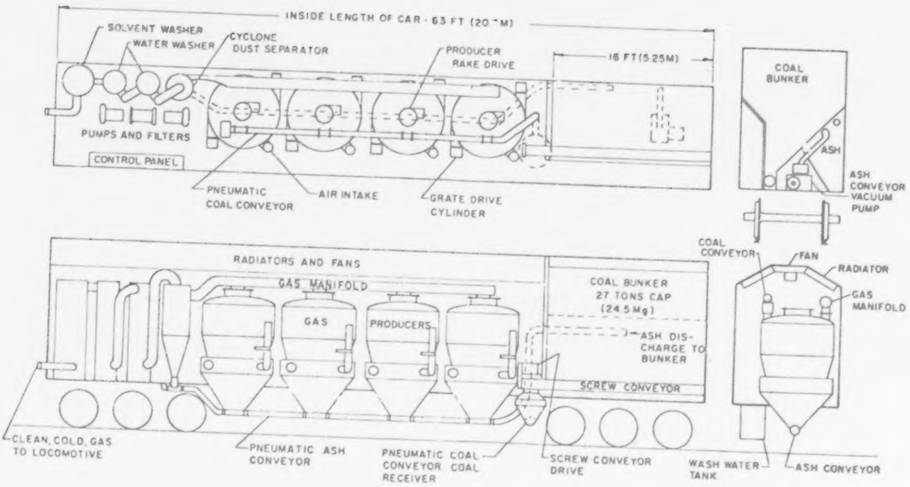

FIGURE 2. Gas Producer Car

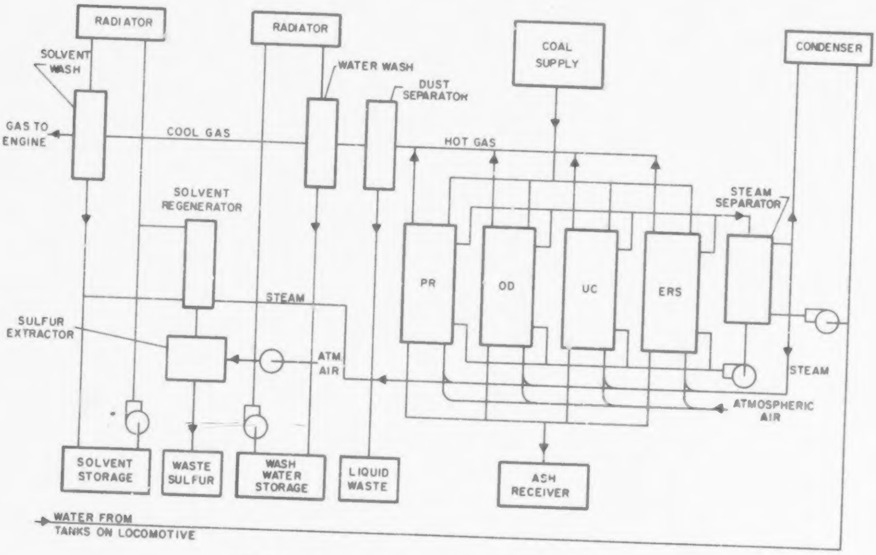

FIGURE 3. Schematic Flow Diagram of Producer Car

Because of the close similarity between the present diesel and the producer gas engine, the latter might better be used in the first generation of locomotives. In the long run, however, the simplicity of the turbine provided a satisfactory combination of efficiency and durability can be attained, will probably make it the ultimate power generator for use with producer gas.

Producer gas engines use spark ignition and require about 50% more displacement than four-stroke diesel or gasoline engines of the same power. To confirm that such an engine can be designed to occupy the same space in the locomotive as a typical diesel, an 18-cylinder W engine, whose cross-section is shown in Fig. 4, was laid out. The necessary increase in displacement within the length dimensions of a 16-cylinder, 2-bank diesel is provided by the third bank of cylinders.

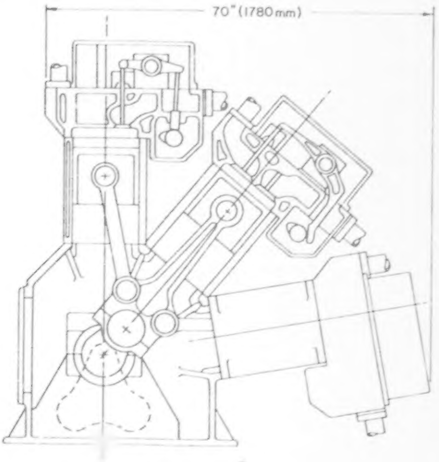

FIGURE 4. Gas Engine Cross Section

WEIGHT STUDY

A preliminary estimate of power system weight was made with reference to the proposed concept. Weight is an important characteristic since it is directly related to the cost of the locomotive, to dead weight of the train and to axle loadings.

Table 4 summarizes the weight breakdown, with closer attention given to the new entity. The gas producer car. To a first approximation, the locomotive itself will weigh about the same as the diesel-electric counterpart. The engine, while of larger displacement than the diesel, would operate at lower pressures and hence would not need to be much heavier. Larger radiators may be needed as a consequence of reduced thermal efficiency.

Weights shown for the gas producers are believed to be realistic since the design is based on known factors. There is some uncertainty as to gas-cleaning equipment since future limits on sulfur emissions are not yet known.

COST STUDY

A major incentive for the use of coal is its low cost compared to diesel fuel. Furthermore, there is reason to expect that this cost ratio will continue to strongly favor coal for the foreseeable future. Fig. 5 was prepared from a report by the Jet Propulsion Laboratory showing estimates of this cost ratio (10). The fuel cost ratio is reduced by the relative efficiencies of diesel and gasified-coal power systems from a factor of five to about a factor of three. However, in the special cases of railroads which have their own properties, the cost ratio can be considerably greater.

Some insight into the possible purchase cost of the fully developed gasified-coal locomotive can be gained from Table 5. The cost per pound of manufactured equipment is known with fair accuracy, and it can reasonably be assumed that gasification equipment costs will fall between powered and non-powered rolling stock. Pilot models or prototypes would, of course, be more expensive. If these relationships hold, then gasified-coal locomotives will cost about 25 to 30 percent more than diesel-electric locomotives.

Fuel cost savings from the use of coal are determined by locomotive duty cycles, power system thermal efficiency and fuel costs per unit heating value. Fig. 6 shows the range of annual fuel cost savings which can be expected from mainline service. The 1982 estimated national average coal price (to the user) is about $1.17 per billion joules ($1.24 per million BTU) heating value (11). From Fig. 6, the saving in fuel cost can exceed $300 000 per year. Such a saving would pay for the estimated cost of the gas-producer car in approximately one year.

Net savings in operating cost would be somewhat less, taking into account the higher cost of maintenance. There would also be a capital cost in providing the necessary wayside coal-handling facilities.

ENVIRONMENTAL ISSUES

At the present time, there are no regulations governing exhaust emissions from locomotives, except for smoke-abatement ordinances. The use of coal gas should completely eliminate smoke emissions.

Complete combustion of gaseous fuel is expected to result in low emissions of carbon monoxide, and because of the low hydrocarbon content of the fuel, hydrocarbons in the exhaust would be correspondingly low. There will be nitrogen oxide emissions as from any air-breathing combustion engine, but these should be less with gas fuel because the compression ratio is moderate compared with that of diesel engines.

The increased use of coal as an energy source has raised some serious problems, not the least of which is the control of the discharge of sulfur compounds into the atmosphere. The authors believe it is easier to remove sulfur compounds from the gas prior to combustion in the engine, than it is to remove SO_2 from the exhaust. Their disposition will be as solid or liquid waste.

Ash likewise will be removed from the process prior to the entry of the gas into the engine. As in

TABLE 4. PRELIMINARY WEIGHT STUDY

ITEM	Est. Wt., kg	Est. Wt., lb
Gas Producer Car, Less Equipment	34 000	75 000
Gas Producer Equipment:		
Gas Producers, four at 13 550 lb (6150 kg)	24 600	54 200
Coal and Ash Conveyors	2 200	4 900
Gas Collecting and Cleaning Equipment	3 400	7 500
Radiators and Fans	1 600	3 500
Auxiliary Power Systems	1 100	2 500
Other Equipment	5 900	13 100
Gas Producer Car Dry Wt.	72 800	160 700
Fuel, Water and Solvents, at Capacity	28 000	61 700
Loaded Weight of Car	100 800	222 400
Locomotive, 3000 hp Mainline Type:		
Dry Weight	152 000	335 000
Water, sand, oil, at capacity	16 500	36 400
Loaded Weight of Locomotive	168 500	371 400
Loaded Weight of Locomotive and Producer Car	269 300	593 800

the case of sulfur, this does not change the amount of material returned to the environment, but this locomotive concept does allow a controlled management of disposal.

CONCLUSION

We believe that the conclusion of this study is that producer gas as an intermediary between coal and the prime mover can provide the performance and reliability of present locomotives with no increase in train personnel, can meet any reasonable air pollution requirements and, most importantly, can take full advantage of the assured supply and low cost of coal as a locomotive fuel.

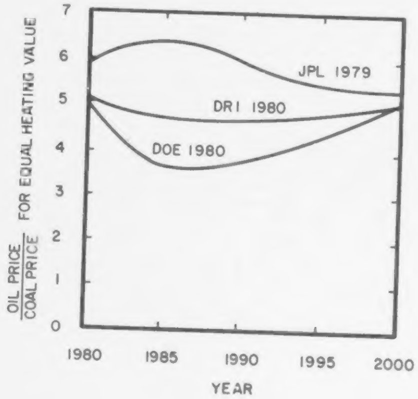

FIGURE 5. Projected Ratios of Oil-to-Coal Prices

From graph of prices in JPL Publication:
81-101 Nov. 1981 (Ref. 10)
DRI = Data Resources Inc.
JPL = Jet Propulsion Lab.
DOE = U.S. Dept. of Energy

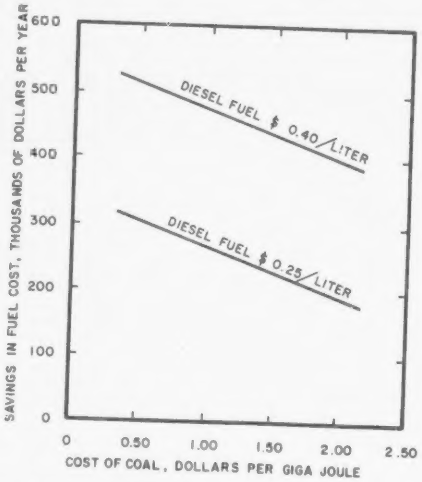

FIGURE 6. Estimated Saving in Annual Cost of Fuel

Assumptions:
- 3600 hours of operation/yr., at 1492 kw (2000 hp)
- Diesel engine thermal efficiency 35%
- Combined efficiency of gas producer and gas engine, 24%
- Heating value of diesel fuel, 39 580 joules/liter (142 000 Btu/gallon)

TABLE 5. PRELIMINARY ESTIMATE OF PURCHASE COST

ITEM	EST. DRY WT. KG (LB)	EST. DOLLARS PER KG (LB)	EST. PURCHASE COST, 1982 DOLLARS
3000 hp Mainline Locomotive	151 900 (335 000)	6.61 (3.00)	1 005 000
Gas Producer Car, less Eqp.	34 000 (75 000)	2.75 (1.25)	94 000
Gas Producer Mechanical Eqp.	38 900 (85 700)	4.81 (2.20)	189 000
Gas Producer Electric Eqp.	-	-	25 000
Combined Cost			1 313 000
Equipped Gas Producer Car	72 900 (160 700)	-	308 000

REFERENCES

1. Daley, J.G. and Kirsch. L.W., "Advanced Locomotive Heat Engines," ASME Paper 82-RT-1, April 1982.

2. Berkowitz, D.A., Benson, W.B. and Withuhn, W.L., "A New Coal-Fired Steam Locomotive for a New Era," ASME Paper 82-RT-2, April 1982.

3. Rentz, R.L., Timbario, T.J. and Renner, R.A. "Solid Fuel Applications to Transportation Engines," SAE Paper 810445, Feb. 1981.

4. Miller, C.L., "The U.S. Coal Gasification Program: Progress and Projects," *Mechanical Engineering*, Vol. 102, No. 8, August 1980, pp. 34-40.

5. Rambush, N.E., *Modern Gas Producers*, Van Nostrand NY, 1923.

6. Degler, H.E., *Diesel and Other Internal-Combustion Engines*, American Technical Society, Chicago, IL 1936, pp. 36-41 and 213-218.

7. Marks, L.S., *Mechanical Engineers Handbook*, 3rd ed, 1930, p. 1256.

8. "Generator Gas, the Swedish Experience from 1939 to 1945" from the Swedish book *Gengas* translated by Solar Energy Research Institute SERI/SP-33-140 Jan. 1979.

9. Skov, N.A. and Papworth, M.L., "The Pegasus Unit" Pegasus Publishers, Inc., Olympia, WA 1974.

10. "Future Fuels and Engines for Railroad Locomotives," JPL Publication 81-101, Nov. 1981.

11. Westerstrom, L., U.S. Dept. of Energy, Washington D.C., Private Communication, Oct. 13, 1982.

12. Walker, Lewis, McAdams and Gilliland, *Principles of Chemical Engineering*, 3rd ed, 1937, p. 173.

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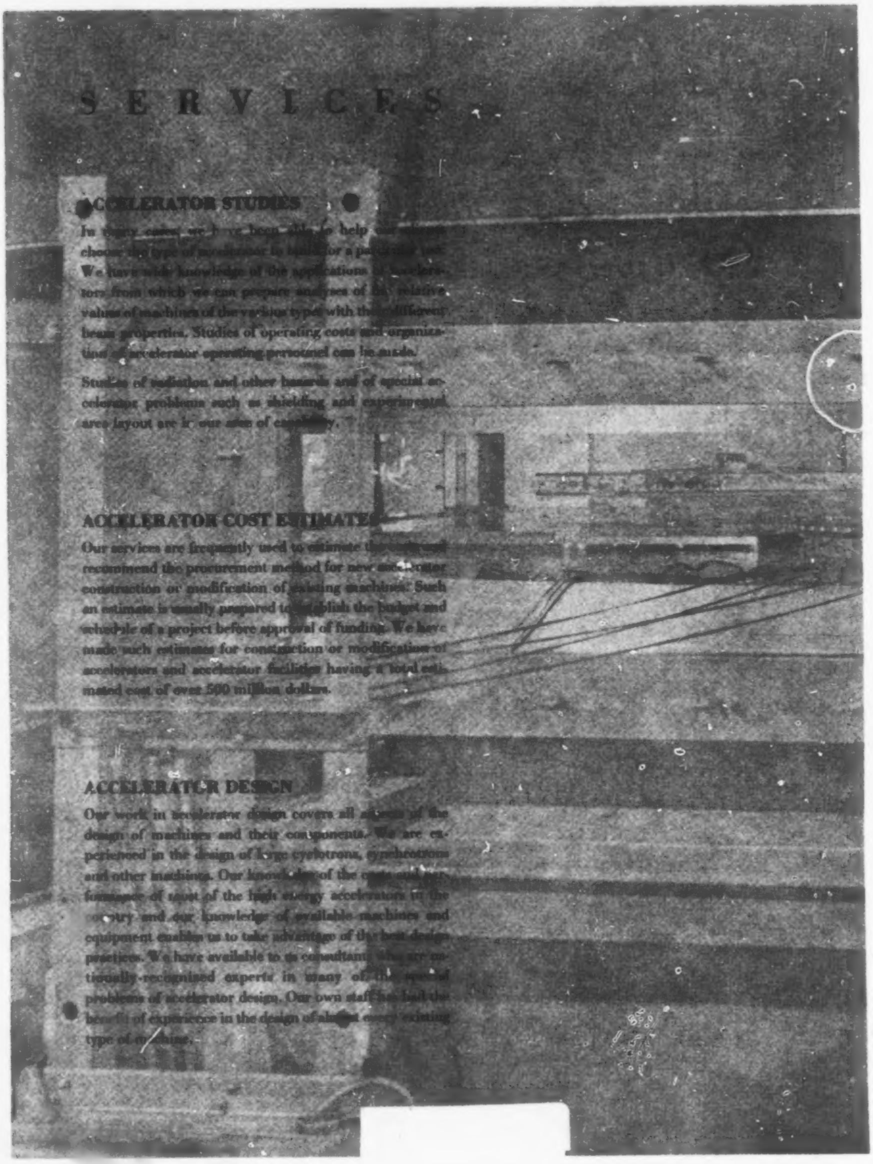
BROBECK CORPORATION is a consulting engineering firm with special capabilities in advanced electrical and mechanical design. One of the specialties of the firm is nuclear particle accelerators. Mr. Brobeck's background before founding the firm in 1957 included twenty years of experience in the accelerator field with the Radiation Laboratory of the University of California at Berkeley.

The company has, since its founding, been widely involved in the study, estimating, design and operation of accelerators throughout the United States and abroad.



SERVICES

ACCELERATOR STUDIES

In many cases we have been able to help our clients choose the type of accelerator to build for a particular use. We have wide knowledge of the applications of accelerators from which we can prepare analyses of the relative values of machines of the various types with their different beam properties. Studies of operating costs and organization of accelerator operating personnel can be made.

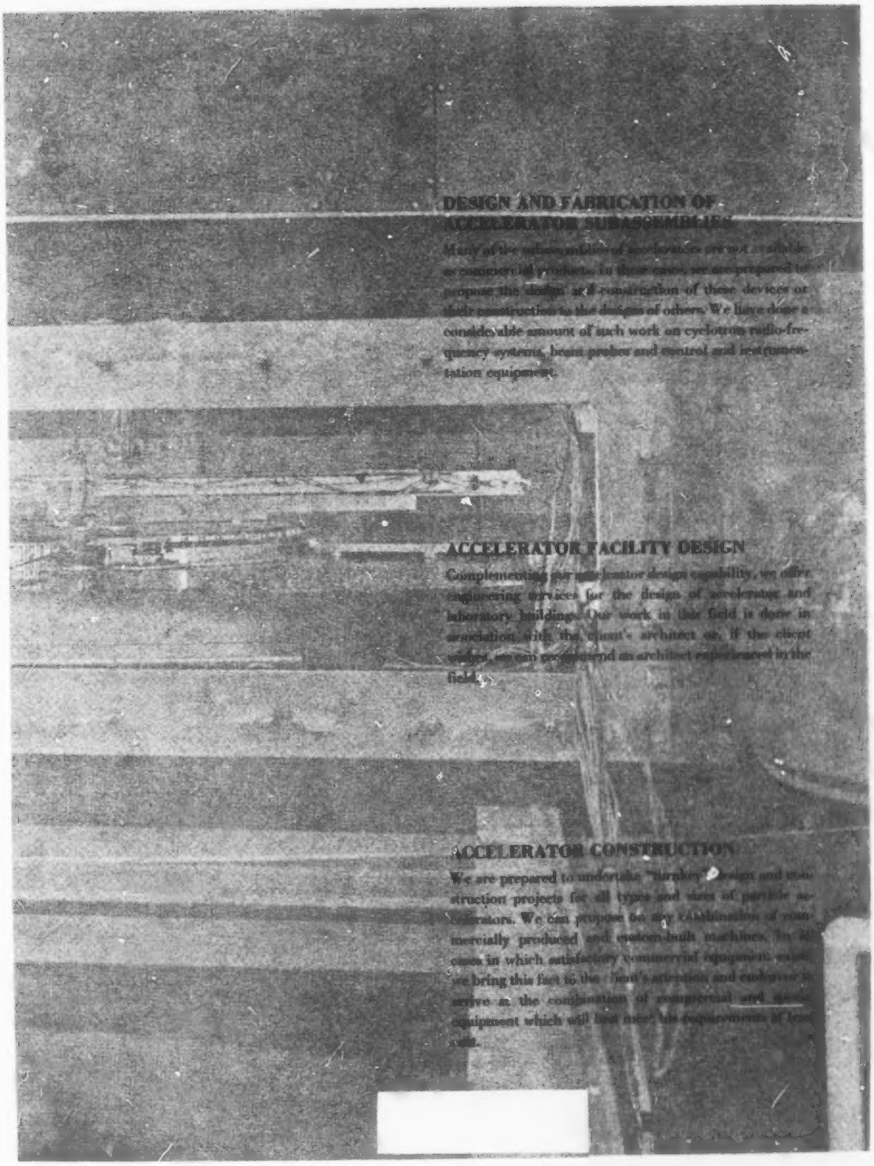
Studies of radiation and other hazards and of special accelerator problems such as shielding and experimental area layout are in our area of capability.

ACCELERATOR COST ESTIMATES

Our services are frequently used to estimate the cost and recommend the procurement method for new accelerator construction or modification of existing machines. Such an estimate is usually prepared to establish the budget and schedule of a project before approval of funding. We have made such estimates for construction or modification of accelerators and accelerator facilities having a total estimated cost of over 500 million dollars.

ACCELERATOR DESIGN

Our work in accelerator design covers all aspects of the design of machines and their components. We are experienced in the design of large cyclotrons, synchrotrons and other machines. Our knowledge of the costs and performance of most of the high energy accelerators in the country and our knowledge of available machines and equipment enables us to take advantage of the best design practices. We have available to us consultants who are nationally-recognized experts in many of the special problems of accelerator design. Our own staff has had the benefit of experience in the design of almost every existing type of machine.



DESIGN AND FABRICATION OF ACCELERATOR SUBASSEMBLIES

Many of the subassemblies of accelerators are not available as commercial products. In these cases, we are prepared to propose the design and construction of these devices or their construction to the designs of others. We have done a considerable amount of such work on cyclotron radio-frequency systems, beam probes and control and instrumentation equipment.

ACCELERATOR FACILITY DESIGN

Complementing our accelerator design capability, we offer engineering services for the design of accelerator and laboratory buildings. Our work in this field is done in association with the client's architect or, if the client wishes, we can recommend an architect experienced in the field.

ACCELERATOR CONSTRUCTION

We are prepared to undertake "turnkey" design and construction projects for all types and sizes of particle accelerators. We can propose on any combination of commercially produced and custom-built machines. In all cases in which satisfactory commercial equipment exists, we bring this fact to the client's attention and endeavor to arrive at the combination of commercial and special equipment which will best meet his requirements at least cost.

ACCELERATOR

ACCELERATOR BUILDING

PRELIMINARY DESIGN

A preliminary design of the various elements of the building, such as foundations, structures, finish, heating and ventilation, is prepared. Outline specifications are written and interfaces are defined. Major decisions which affect the overall design are studied in sufficient detail to provide answers to all pertinent questions. Cost estimates and tentative schedules are included. The AEC designates this work Title I Services, and the Navy denotes the result of this work a Preliminary Engineering Report.

FINAL DESIGN

Final design drawings and contract documents for the building, utilities and other facilities are prepared. Unit construction cost estimates are usually made at this time. Final schedules are submitted for approval.

ACCELERATOR PROJECT MANAGEMENT

PROCUREMENT AND INSTALLATION SERVICES

Systems and components, as described by their design drawings and contract specifications, are purchased from commercial fabricators on a competitive fixed-price basis where possible. Some components are developmental in nature. The fabrication of these components must be coordinated by the design engineers. Evaluation of vendor qualifications, technical inspection and witnessing of tests in the vendor's plant is provided. Drawings are completed to show the as-built condition. The issuing of purchase orders, contract administration, expediting and routine inspection can also be furnished.

Installation of the accelerator is usually accomplished by a combination of contractors, local tradesmen and operating staff. Technical supervision, direction and operations required during installation, must be performed by personnel with specific related experience.

OPERATION AND MAINTENANCE SERVICES

The operation of the accelerator for research purposes can be provided on a contract basis. Operating crews will be hired and trained and operation and maintenance manuals provided. Maintenance technicians will be trained under an engineer not only familiar with the machine itself but capable of designing minor modifications required by specific experiments.

COURSE OF CONSTRUCTION SERVICES

Review of shop drawings and general architectural and technical supervision are provided during construction. Drawings are completed to show the as-built condition. Complete job responsibility, including [illegible] inspection and job [illegible] [illegible]

ACCELERATOR STUDIES

ACCELERATOR COST ESTIMATES

ACCELERATOR DESIGN

ACCELERATOR SUB-ASSEMBLY DESIGN AND FABRICATION

ACCELERATOR FACILITY DESIGN

ACCELERATOR CONSTRUCTION

ACCELERATOR PROJECT MANAGEMENT

Senator WARNER. You have cery skillfully and tactfully outlined what I perceive as a certain amount of reluctance on the part of the rail systems to put their money into these new R&D projects. Then this bring us to the question of reexamination of the Federal funding aspect. What would be a prototype Federal funding program, as you'd like to see it? Might such a prototype program have the U.S. Government in partnership with three firms such as yourself to develop three types of these engines to see which one is the best.

Mr. THOMAS. I think we'd have to be—I come basically from a free enterprise background and I have to be careful the way I deal with that. Also, I have been close enough to the transportation industry to have watched the development of the bus some years ago and I'm certainly not prepared to recommend that we try a program like that again.

Senator WARNER. What was that?

Mr. THOMAS. It was a program that the DOT developed—a new bus.

Senator WARNER. Oh, the bus! Yes.

Mr. THOMAS. And coming out here on the airplane, I began to think about how we might attack this problem. There are only two or three things that really struck my interest. Perhaps that's because of limited background with the various Federal financing programs. One of the things I ran into when I started to look around at financing this project is that there is some substantial concern and question as to whether there are energy tax credits, for instance, available for burning coal as opposed to diesel oil. I certainly think that ought to be clarified. The experts that I was talking to seemed to have some question and they are working on an answer for me in that area.

Senator WARNER. Would you be kind enough to supplement your testimony on the record with the answer that you get there?

Mr. THOMAS. I'd be happy to do that.

Senator WARNER. Unless you consider it proprietary, I would invite you to.

Mr. THOMAS. No. I'd be glad to.

Senator WARNER. How soon might that be available?

Mr. THOMAS. I hope it will be available in the next 2 weeks. They seem to have no question that we're going to burn rice hulls or something like that—laughing—and we'd have no trouble with the exergy tax credit. There seem to be some questions if all we are doing is replacing diesel fuel with coal and if there was no net energy saving, and we are working on that presently.

The other possibility that runs rather loosely through my mind is the one that you kind of alluded to, I think. I think this project lends itself nicely to an R&D partnership. I think that perhaps this is an area in which we maybe ought to sit back and take a lesson from some of our counterpart around the world, especially Japan. The way they get involved in major prototype development for some considerable years in capital equipment around the world and ran into it in my product area in Japan. It might be a place where the Federal Government could participate in an R&D partnership on a funding basis but, at the same time, retain a financial interest that would permit them to recover their investment before the item is sold or put into service.

Senator **Warner**. A royalty payback?

Mr. **Thomas**. Sure. I don't see why we can't develop a mechanism to do that. It doesn't appear to exist at this time. I think its an area where we ought to really look especially where a product like this not only has an economic benefit for a very major and vital transportation link but for anyone who has worked or traveled in the Middle East can well attest that our oil supply from that part of the world is in fairly delicate condition almost continuously and the possibility that could be cut off in short order is very real. I think there are ways or there should be a major effort to encourage less dependence on that. This is one way, I think, and its terribly important.

Senator **Warner**. What would be the magnitude of this prototype program—let's arbitrarily say—if the Government has four projects. What would be the extent of Government participation and over what period of time?

Mr. **Thomas**. I believe my colleagues mentioned some numbers here today—well, the whole spectrum when we've finished here this afternoon, I think. Certainly the range is now from about $7 million to somewhere around $45 million, I think, in this room represented by relatively small companies that have some innovative ideas in this area. I certainly think that I am within that framework if the Government were to pursue three units and one has to assume you're looking at $100 million to $150 million to a commercial prototype. I feel fairly strong about that. I've seen people propose—in fact my own company started out thinking in terms of a study kind of a contract followed by an engineering prototype. I really think that the project—one could always put milestones and shut it down. I really think that the overall goal of the project should be to produce a commercial prototype that has high reliability for sale in the marketplace.

Senator **Warner**. I have a very modest engineering background. In my defense, for years I have been involved in prototype work. I was impressed today by the comments that we'd better walk before we run and perhaps build some test bed models and then evolve into the rolling stock. Any comments on that?

Mr. **Thomas**. I certainly—in the comments I outlined—I feel very strongly that certainly in this technology that there is a need for some test bed modeling. I don't think its very extensive but there are some things that you can prove without running around on a track and I think we ought to do that. Demonstrate and fine tune it. When we get on tracks we ought to have the problems that can be solved on the bench worked out. I think they are straightforward engineering problems. I'm talking about bench testing and doing some locomotive work in parallel with designing the program so that you could end up with a commerical prototype in a 3- to 4-year period.

Senator **Warner**. A rolling operating one?

Mr. **Thomas**. You would have some operating probably in a couple of years. But not one that you could take from Roanoke, VA, to Oakland, CA. I would think that you could achieve that if you had the money and the technical talent.

Senator WARNER. But 5 years is the outer limit in your judgment that it would take to achieve this thing?

Mr. THOMAS. I think so.

Senator WARNER. And we can put one of these things on the tracks, one or two variations—can we do it?

Mr. THOMAS. I think so.

Senator WARNER. Thank you. Was there anything else you wished to add?

Mr. THOMAS. No. Thanks very much.

Senator WARNER. Mr. Thomas, thank you. Did you come all the way from Berkeley?

Mr. THOMAS. Yes sir, I did.

Senator WARNER. Perhaps you could supplement the record upon futher reflection and perhaps consultation with your colleagues as to how a Federal subsidy program might be structured.

Mr. THOMAS. I'll be glad to do that.

[Subsequent to the hearing Mr. Thomas submitted the following:]

BROBECK
CORPORATION

December 20, 1983 File: 8400-857-1

The Honorable John W. Warner
The United States Senate
Senate Office Building
Washington, D.C. 20510

Dear Senator Warner:

At the hearing on November 28, 1983, on the Reintroduction of Coal as a Fuel for Locomotives, you asked that I send you some additional information on the clarification of the energy tax credits as they apply to the conversion of locomotives from diesel fuel to coal and suggest some ways by which the government might stimulate this conversion.

You will recall my belief that the conversion will ultimately take place because of the large economic incentives to the railroads and the abundance of coal in our country. However, because of the vital importance of our rail system to the security of the United States and because of the lead time required to produce a commercial prototype acceptable to the railroads, stimulation by the government is clearly in the public's best interest. The railroads are likely to convert much more quickly if they can road test an operating locomotive than if they must individually fund the development of one or another prototype. The locomotive manufacturers, too, are more likely to invest in the sale and manufacture of coal-burning locomotives if some of the development risk is removed from the project.

Our own analysis suggests that in spite of the relatively large size of the locomotive market, the railroads historically have been reluctant to try new major systems from unproven manufacturers. This suggests that any small but innovative company must find a way to team with one of the major locomotive manufacturers if it is to be an active participant in the conversion. Since the project is an ideal R&D partnership, our strategy includes the participation of a major manufacturer with a commitment to sell and manufacture the resultant product. We will be in a position to reasonably discuss our project right after the first of the year.

I have enclosed a copy of a letter from Deloitte, Haskins & Sells which deals with the existing R&D tax treatment and recently expired energy tax credits. Certainly, since this country has an abundance of domestic coal, the Congress should assure that the conversion from oil to coal continues to receive incentive tax considerations. As you are well aware, Senator, we are far from a solution to our long-term energy needs.

(415) 524-8664

1235 Tenth Street
Berkeley, CA U.S.A.
94710-1593

On a broader scale, the government might directly, or through one of the major locomotive manufacturers, finance or guarantee the financing through commerical prototype of two or three locomotive systems. The resultant product must be a reliable machine capable of entering regular railroad service operated by current railroad personnel. The funding should be sufficient for a project to reach the commercial level of performance and for the developing team to publicize and demonstrate the system. The over all goal of each project must clearly be the commercial sale of equipment both in the U.S. and overseas.

To support this development, the government might receive warrants in return for their guarantee much like it did in the Chrysler case. Or, it might receive royalty payments to provide for the recovery of the government's investment as locomotive units are sold into commercial service. The basis of the royalty should be equal in each project to the total investment, thus, assuring repayment if only one project succeeds. Otherwise, the project should be largely free of government constraints. The government's participation should be viewed as an investment the result of which will be a return on the investment and the acceleration of the conversion from diesel to coal as a fuel for America's locomotives. Additionally, of course, we would expect to see new jobs and taxes from one of our most vital "smokestack" industries.

We believe that our gasified coal locomotive is a sound approach to the conversion of our locomotive fleet from diesel oil to coal and that with a relatively minor stimulus from the government, we can have significant numbers of locomotives operating on the railroads of America within ten years.

We thank you for the opportunity to outline our project and look forward to working with you to make it happen.

Sincerely,

Kenneth M. Thomas

Kenneth M. Thomas
President

KMT:jw

Enclosure: Copy of Deloitte, Haskins & Sells letter
dated 12-16-83

cc: Mr. Roger A. Sindelar

**Deloitte
Haskins+Sells**

One Kaiser Plaza
Oakland, California 94612
(415) 452-0250
Telex 340336

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Wm. BROBECK & ASSOCIATES.

December 16, 1983

Mr. Kenneth Thomas, President
Brobeck Corporation
1235 Tenth Street
Berkeley, California 94701

Dear Mr. Thomas:

This letter is in response to our conversation concerning the availability of energy tax credits for expenses incurred in converting railroad locomotives from burning diesel fuel to burning coal. It is our understanding that diesel burning locomotives would be modified to burn coal as their only fuel. The project is at a discussion stage only and neither formal engineering studies nor governmental applications have been completed.

As a general rule, taxpayers are entitled to a 10% investment tax credit on investments in depreciable tangible personal property. In addition to the regular investment credit (§§ 38 and 46 Internal Revenue Code of 1954 as amended (IRC)), business taxpayers may qualify for an additional investment credit of either 10% or 15% for investing in certain defined energy property. One such type is "alternative energy property" (§48(1)(3)IRC).

The phrase "alternative energy property" includes certain property that uses a fuel or feedstock other than oil or natural gas. Such property includes equipment designed to modify existing equipment if, as a result of the modification, the alternative fuel comprises at least 25% of the fuel or feedstock of the existing equipment (§48(1)(3)(A)(iv)IRC).

Based on the above discussion, it appears that the energy credit could be available. However, the credit for investments in "alternative energy property" expired at the end of 1982. Section 46(a)(2)(B)(iii) IRC provides that the expiration date would be extended if 1) the property is part of a project with a normal construction period of two years or more, and 2) before January 1, 1983 all engineering studies on the project have been completed and applications for all environmental and construction permits required under federal, state or local law for the project have been filed. In addition, the law contains other specific time references for such a project.

It appears, therefore, that although the proposed expenditures could have qualified for the energy credit, the project will not qualify because the required acts necessary to extend the credit have not occurred.

You indicated that the cost of developing and manufacturing the equipment necessary to convert an existing diesel locomotive to burning coal could be $40 million. You further indicated that such an investment may only result from a joint venture of two or more companies interested in such a project.

If the joint venture takes the form of a partnership for tax purposes, any credits generated would generally be passed through to the various partners. For instance, if there are four equal partners any tax credits would be divided, with ¼ of the total going to each partner.

A difficulty arises in qualifying for energy credits where the partnership is developing equipment or processes to modify other equipment. An investment in property designed to modify existing equipment qualifies for the energy credit; thus a railroad purchasing equipment designed to modify locomotives would be entitled to the energy credit. However, the costs incurred in developing the equipment to sell to the railroads to enable them to modify their locomotives would not qualify for the energy credit because the equipment is not used in the actual modification. Furthermore, the costs to develop the equipment will probably not qualify even for the regular investment credit except to the extent tangible personal property is either purchased or constructed.

Instead of the energy credit, the costs of developing the equipment may qualify for the R & D credit (§44F IRC). This credit equals "25 percent of the excess (if any) of - (1) the qualified research expenses for the taxable year, over (2) the base period research expenses. "(§44 F(a)IRC).

There are specific definitions of the phrases "Qualified Research Expenses" (§44F (b)) and "Base Period Research Expenses" (§44F (c)). A major factor limiting the use of the R & D credit contained in the definition of qualified research expenses is the requirement that the expenses are paid by a taxpayer in "carrying on any trade or business of the taxpayer". Thus, a partnership specifically formed for R & D purposes will generally not be able to avail itself of the credit because the research is not incurred in carrying on a trade or business of the partnership.

Proposed Reg. §1.44F-2(a)(4) discusses the rules applicable to R & D partnerships. These proposed regulations contain an exception to the general rule for certain joint ventures A) where all the partners are entitled to the results of the research and B) the following is true with respect to each partner: "If the partner had carried on the research that was in fact carried on by the partnership, all the research expenses paid or incurred in carrying on the research would have been paid or incurred by the partner in carrying on a trade or business of the partner." (Prop. Reg. §1.44F-2(a)(4)(ii)(B)).

Because the availability of these credits depend on particular circumstances, we are not able to opine that these credits are or would be available to any particular taxpayer or joint venture. For instance, if the modification did not alter the fuel usage sufficiently, then the energy credit would not be available (ignoring the issue of expiration); or if the cost of developing the process didn't exceed "base period research expenses," then the R & D credit would not be available. Nevertheless, it appears that a joint venture formed, by either railroads or locomotive manufacturers, specifically to develop this equipment, could qualify for R & D credits which would be passed on to the individual partners. Furthermore, a company purchasing the developed equipment would apparently qualify for the energy tax credit (ignoring the issue of expiration).

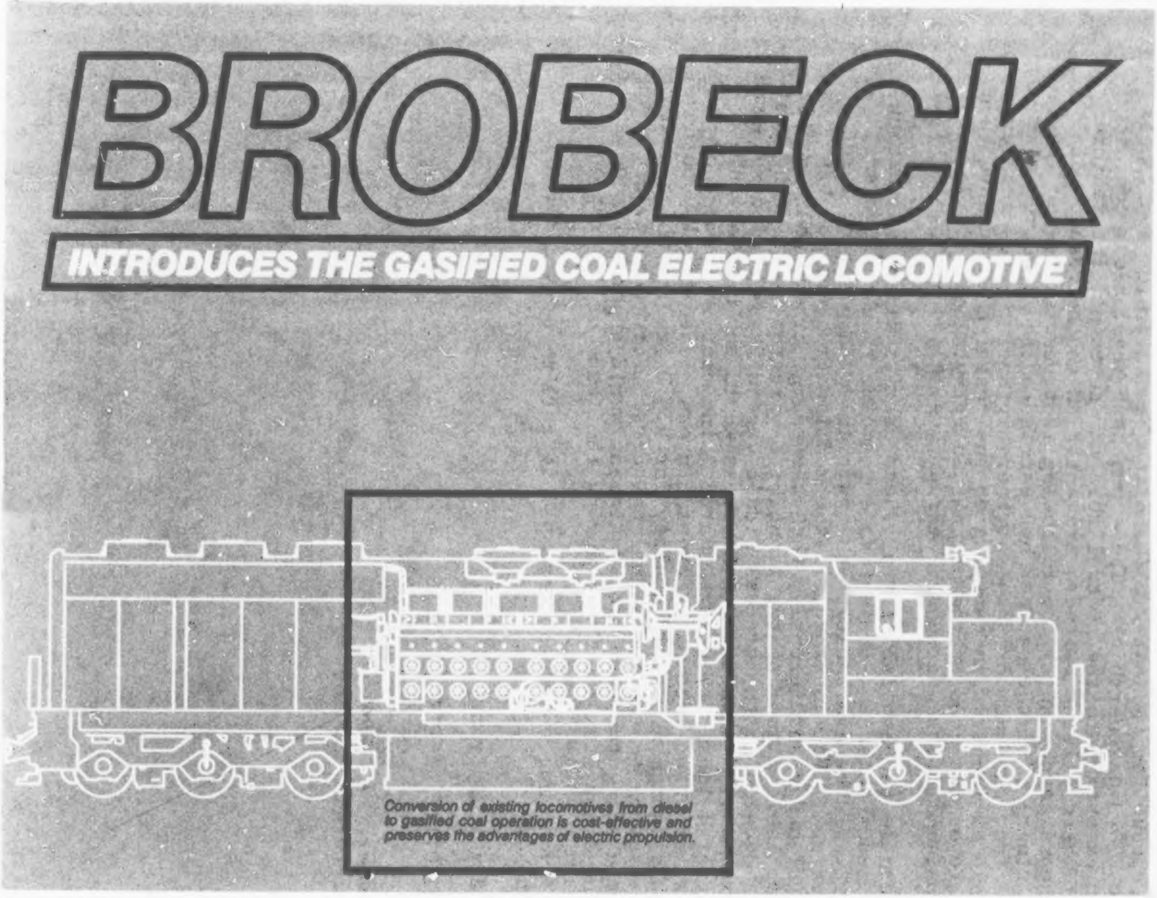
If you have any questions, please call me or Mr. Ralph E. Anthony.

Very truly yours,

DELOITTE HASKINS & SELLS

Kenneth B. Everett

Kenneth B. Everett



BROBECK

INTRODUCES THE GASIFIED COAL ELECTRIC LOCOMOTIVE

Conversion of existing locomotives from diesel to gasified coal operation is cost-effective and preserves the advantages of electric propulsion.

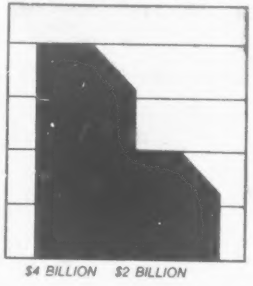
THE GASIFIED COAL ELECTRIC LOCOMOTIVE ALTERNATIVE

1. Cuts Fuel Bills in Half

The cost of fuel is the largest single expense in running the nation's locomotives today. Diesel fuel prices soared 135% between 1978 and 1980, and with increased rail traffic, fuel bills rose from about $1.5 billion to $4 billion in that time period.

Diesel fuel now costs $6.50 per million BTU of energy, and substantial increases are anticipated in the next decade. Coal, at one quarter the cost, is an attractive alternative today; and as its cost is expected to rise much more slowly than diesel fuel's, it will offer even greater cost savings in the future. While it is only half as efficient as diesel fuel, coal affords a healthy 50% savings now, and should prove even more cost effective in the years to come.

AMERICAN RAILROADS' FUEL BILL



2. Ends Dependence on Foreign Oil

"To ruin the consumer countries, we only have to reduce our production ... the price would rise not by 35, but by 40, 50, even 80 percent."

— Shaikh Yamani, Saudi Oil Minister

With an estimated 400 billion tons of coal available in economically recoverable reserves, America has the energy equivalent of 1,800 billion barrels of oil—an ample energy supply for the next 100 years. Converting to coal would eliminate the railroad's dependence on imported oil, so the transportation needs of our nation's industry and defense would no longer be vulnerable to fluctuating costs and interrupted supplies from foreign sources. Our own oil resources could be put to better use in petroleum products for the nation's industrial needs.

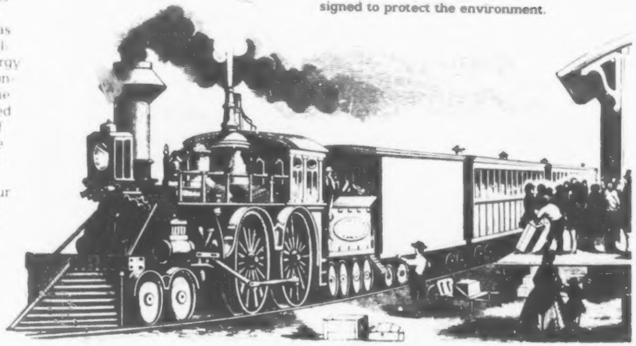
3. Burns Coal Cleanly

Today's modern, coal-burning locomotives have little in common with the old-fashioned "iron horse" steam engines, which spread smoke and cinders throughout the countryside. Gas-producer combustion of low sulphur coal eliminates steam, smoke, and cinders, reduces nitrogen oxides to levels below those of current diesel locomotives, and brings sulphur dioxide emissions to well within environmentally acceptable limits. Ash, sulphur, and liquified waste are efficiently contained in the system until removed at the end of the run. And because the system is fully enclosed, it operates quietly, as well as cleanly.

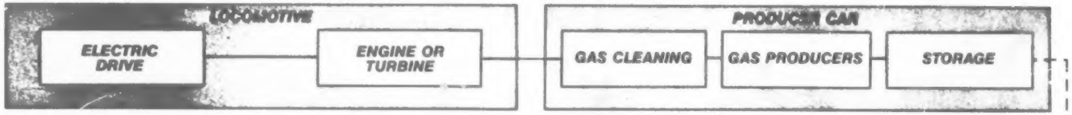
4. Can Convert Existing Fleets

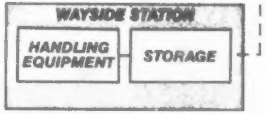
Brobeck's gasified coal technology can be applied to existing locomotives, eliminating costly replacement of active fleets. Existing diesel engines will be replaced with gas or turbine engines designed to burn coal gas, a procedure far less expensive than purchasing a new coal-burning locomotive. The conversion process will preserve thousands of locomotives that are in use today whose oil-burning engines now face obsolescence. Conversion takes advantage of the cost savings of coal use, while still preserving the advantages of electric propulsion.

Unlike the romantic 19th century steam engines, Brobeck's modern, coal-burning locomotives are designed to protect the environment.



HOW THE BROBECK GASIFIED COAL SYSTEM WORKS





Elements of the System

The Brobeck gasified coal system uses coal to generate gas which is burned in an engine or turbine, driving the locomotive through a conventional electric generator-motor system. Gas production takes place on the unmanned producer car, which serves as a tender car directly behind the locomotive. Propulsion and braking are controlled by programmable microcomputers, or directly by the engineer. Microcomputers also play an important role in scheduling maintenance, monitoring all the supply and waste systems, and warning of any irregularities. The system includes efficient cleaning equipment to remove sulphur and other impurities from the gas before it reaches the engine. Liquid and solid waste products are collected and stored on the train, and at the end of the run are discharged cleanly in containers. The coal itself is loaded in containers, preventing any coal dust from escaping.

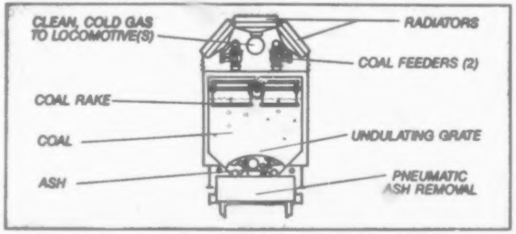
The Gas Producer

As shown below, the gas producer is essentially a tank partially filled with coal. Air, into which water is sprayed, enters at the bottom, and the combustible gas leaves at the top. The air and gas flow is produced by suction from the engine, so that the producer operates at slightly below atmospheric pressure, and all leakage is inward.

Unlike old-fashioned coal-burning methods, the Brobeck system is computerized and fully automatic. The gas output follows the demand for power as controlled by the engineer's throttle or the computer program. Coal feed and waste removal follow the power demand under control of the microprocessors.

Cleaning the Gas

When the gas leaves the producers at high temperature, it contains dust, ammonia vapor, sulphur, and heavy hydrocarbons which, on cooling, condense to tar. The Brobeck design uses a cyclone separator to remove the dust and tar. The dust-tar mixture is re-injected into the high temperature zone of the gas producer where its combustion adds to the heating value of the gas. Beyond the cyclone separator the gas is cooled, transferring its heat to water, which is in turn cooled in radiators on the top of the car. Sulfur, which is almost entirely in the form of hydrogen sulfide, is removed by solvent extraction. The effluent gas delivered to the engine or turbine is cleaner than diesel oil.



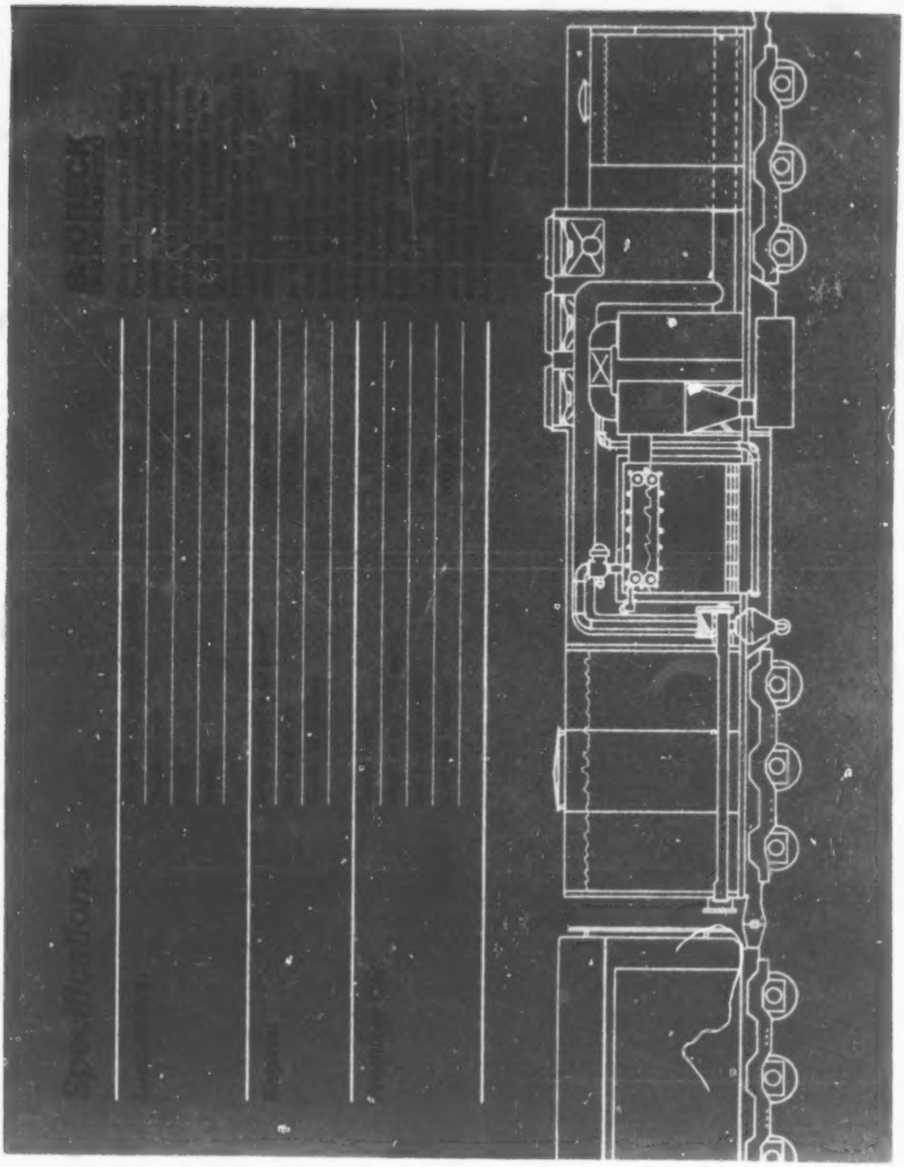
Wayside Equipment

Major railroad yards would be equipped with coal and water supplies and waste disposal facilities. All materials are handled cleanly and efficiently in containers without the use of manpower. The travel distance between loading points would be the same as with present main-line diesel locomotives.

BROBECK

Engineering a Better Future for America's Railroads

1235 Tenth Street
Berkeley, CA U.S.A. 94710-1593
(415) 524-8664



Specifications

Senator WARNER. I want to express my appreciation to Mr. Ross Rowland for accommodating the other witnesses. Also, I take note of the fact that Mr. Rowland and I were in partnership during the bicentennial period when he performed the impossible and ran the Freedom Train across our land. So I know that you can get things done that others view as totally impossible.

STATEMENT OF ROSS ROWLAND, CHAIRMAN OF THE BOARD, AMERICAN COAL ENTERPRISE, INC., NEW YORK, NY; ACCOMPANIED BY DR. DAVID BERKOWITZ, VICE PRESIDENT, ENGINEERING, AKRON, OH

Mr. ROWLAND. Thank you, Senator, for your faith. I hope that I don't betray it. We are making, we think, an honest yeoman's effort to solve this problem of getting our strategically most important form of transportation—the railroads back to coal. A lot of what I was prepared to say has been said for me by my colleagues who went ahead of me. So let me just, if I may, quickly go through some slides which we hope will give you an idea of our project.

As background, let me tell you that—I guess its appropriate we go last today because to the best of my knowledge our little company which we started in 1980 on a quest to answer the question: Could we put the railroads back on coal? I think it therefore has the honor of being the longest one in the race. I hope that if that's true, we were first out of the starting gate and that we're also the first over the finish line.

I think that we have something that hasn't been talked about much today. We have put a lot of the $2 million that we have spent to date into making sure that we designed as simple a machine as possible and a machine that would fit into—readily fit into the current operation and maintenance modes of the railroads. And a machine that will burn run-of-the-mine coal in a nonfluidized bed combuster furnace which is far simpler than the one we just saw, in our opinion. And a machine that can be—the final engineering done on. The prototype built and tested and the production model in production—on the production line in 48 months.

About 16 months ago, the JPL Laboratories at a cost to the Federal Government of approximately $1 million did a study that took—that cumulatively involved about 10 man-years of effort. And they looked at our locomotive and they looked at the improvements that they felt would be possible for the diesel electric locomotive to adiabatic-cycle diesels, to just about every possible alternative and their conclusion in November 1981 when they published the study was that first generation steam which was the ACE3000 that was the way to go. There's a slide in here that shows you why. Just before we get to the pictures, let me tell you that we have spent the last 18 months working hand in glove with two of America's major railroads, one of which is boilermakers and are forming a partnership which has recently had some difficulty because one of the partners earnings were sharply lower and they decided, among other economy moves, to cut out this project. So we're back to trying to replace them in the picture in order to fund the $45 million prototype effort totally in the private sector. And we're hopeful of being able to do that. As was said by one or two of the folks that went ahead of me, I share the sentiment that if humanly possible we would prefer to do this in the private sector. And we think that the economics are so compelling as shown before and as I will show in a minute, that it should be able to be done without Government funding. I'm here today, Senator, to tell you whether the ACE wins the race or someone else does, in my mind there is no question whatsoever that within the next decade the fleet of locomotives in this country will in one form, or maybe several forms, switch back to coal. That's my prediction and opinion. Let me just go through the pictures quickly.

This is a side view of our locomotive which—on the right is the power unit and on the left is what we call the support unit. It develops 3,000 horsepower at 1 mile an hour and the power curve of the steam engine is exactly the opposite of a reciprocating steam engine and is about the opposite of a diesel electric. In other words, its power peak is in the 45-50 mile-an-hour range where it peaks out at something over 4,000 horsepower whereas the diesel is strongest at 1 mile an hour and gets progressively weaker as it gets faster.

There's the bottom line of our project and frankly, all the others that you've seen today. Selfexplanatory. Price of diesel fuel in terms of dollars per Btu versus the price of coal in terms of dollars per Btu. In the case of our locomotive, Senator, it became economically feasible sometime in the middle part of 1979 when the oil price per Btu got about $4 per million versus coal. That's where the gap made our locomotive economic sense.

This slide shows the cost of owning diesel locomotives. The statistics that we've gathered from the Association of American Railroads. The white being 1980 and the blue being 1978 and you can see the dramatic increase just in those 2 years in the fuel category versus the relatively small increase in all the other categories.

This is the bottom line of the result of the Department of Energy JPL Study that was published in November 1981. As you can see, it lists the various alternatives that they explored, the fuel they used, the annual life cycle cost per unit and the time for commercial production. Our locomotive, the ACE3000, in that report is called first generation steam on this slide. Again, I think its pretty self-explanatory. It shows very clearly that our locomotive has by far the quickest time for commercial production. Far and away the best cycle economics. And to us, it makes like the adiabatic diesel you see there that burns oil shale distillate. $800,000 a year life cycle cost. Fourteen to twenty years from now before we can get into production, et cetera, et cetera.

This is a slide that shows our locomotive and how we believe, based on the engineering tests that we've done, it will reduce the unit coal train operating costs for the railroads of this country. On the right-hand side it shows our best estimates of the relative cost of maintenance of our locomotives versus comparable fleet of diesel electrics to do the same job.

The bottom line in 1981 dollars. Net present value of coal versus diesel with a 6-percent yearly discount rate on a 15-year horizon. Our engine comes out with an internal rate of return of 86 percent a year.

This is a slide that shows locomotive 3450 in service on the South African railways taken about 2 months ago. And the reason I show it to your is to show you it's pulling a fully loaded goods train uphill in electrified territory. One of the things that we've spent a lot of our time and effort on is we have literally gone around the world to find the designers and engineers—the very few that exist today—that have had actual hands-on railroad locomotive design and experience. And the top man in the field is now a 65-year-old gentleman by the name of Dante Porta. Mr. Porta, Senator, was one of the three principal disciples of a Frenchman who has now passed on named Andre Chapelon (sic). Mr. Chapelon was famous in the world in the late 1940's and early 1950's for his work in France and Germany in increasing dramatically the thermal efficiency of conventional steam engines. Dante Porta has spent the last 30 years in Argentina and South Africa refining and expanding on those theorems.

[The prepared statement of Mr. Rowland follows:]

Testimony of

American Coal Enterprises Inc.

Presented at
FIELD HEARING
Room 403 Federal Building
210 Franklin Road, S. W.
Roanoke, Virginia
November 28, 1983

THE ACE-3000 COAL-FIRED STEAM LOCOMOTIVE

Mr. Ross Rowland	Dr. David A. Berkowitz
Chairman of the Board	Vice President - Engineering

American Coal Enterprises Inc.
2185 Dow Drive
Akron, OH 44313

American Coal Enterprises, Inc. (ACE), has proposed and completed the initial design for the ACE 3000, a modern, clean, efficient, and computer controlled coal-fired locomotive that is operationally compatible with current U.S. railroad practice. The ACE organization comprises railroad people, as well as experts in the mechanical engineering and combustion arts. In addition, initial conceptual design of the ACE 3000 locomotive was done with assistance from operating and maintenance personnel of a major U.S. railroad to insure market acceptability of the locomotive.

~~The~~ ACE project has attracted substantial interest from U.S. railroads, as well as heavy manufacturers, and the investment community. Negotiations are continuing in order to assemble the funds necessary to complete development and testing of prototype locomotives within three years.

ACE is convinced that the ACE 3000 represents the right technology at the right time. Coal is one of the prime commodities hauled by the railroads. It makes no sense to burn imported oil for the purpose of hauling domestic coal. The ACE 3000 locomotive will burn the same coal that's carried in the unit coal train, with no further crushing, grinding, or other treatment. It will burn cleanly and efficiently using proven technology.

The significant aspects of the ACE 3000 project that we wish to emphasize for these hearings in Roanoke are summarized in Table 1, and will be discussed more completely in the testimony following.

TABLE 1

KEY ASPECTS OF THE ACE 3000 PROJECT

1. Fleet operation of ACE 3000 locomotives will make a major reduction in railroad fuel cost;
2. The ACE 3000 project is based on proven technology at minimum technological risk;
3. U.S. railroads represent a significant potential market for Virginia coal; and
4. The use of coal as a rail fuel will have a beneficial effect on the acid rain situation.

1. Railroad Fuel Costs

Figure 1 summarizes information available from the U.S. Energy Information Administration regarding coal and diesel fuel prices. At the present time, energy in diesel fuel is approximately six times more expensive than energy in coal (average price delivered to utilities). As a primary shipper of coal, the railroads often have access to coal at the mine. That is, their price for energy would more typically be the value at the mine-mouth, rather than the delivered price to power plants. In 1983, the typical delivered price for coal depicted in Figure 1 is $1.35 per million BTU. Mine-mouth prices range from approximately $.40 in the west to $1.10 in the east.

Historically, energy costs were only a small part of railroad operating expense. Today, according to testimony offered at this hearing by Mr. Hobart Scott, Vice President-Motive Power for the Norfolk-Southern railroad, fuel accounts for 9.4% of his railroad's operating costs. The effect of fuel costs are even more dramatic if the comparison is restricted only to the expense of maintaining and operating the locomotive fleet. Figure 2 summarizes cost figures for diesel locomotive ownership assembled by the Association of American Railroads for road locomotives on Class-I railroads. In 1978, fuel cost had already risen to approximately one-quarter of ownership cost; by 1980, it had risen to one-half. That is, the cost of fuel for a diesel locomotive is equal to all other costs combined (including crew, servicing, maintenance, shops, facilities, insurance, depreciation, and leasing). Any reduction in fuel cost, either directly or indirectly through improvement in locomotive efficiency, has a direct effect on the cost of locomotive operation. The most dramatic effect would result from conversion from diesel fuel to coal, which in accordance with Figure 1 could be at least a six-to-one reduction in fuel cost assuming equivalent locomotive efficiency.

It is interesting to compare the situation today with the period after World War II when the railroads converted from coal burning locomotives to diesels. At that time, diesel fuel was two or three times as expensive as coal for equivalent energy.* In 1947, the cost for coal was $.16 per million BTU, and for diesel fuel $.55 (reference: J. T. Warren, "Study of

Railroad Motive Power", ICC Bureau of Transport Economics and Statistics, May, 1950). Nonetheless, conversion to diesels reduced the total fuel bill because the diesel locomotive was considerably more efficient and productive than the coal-fired locomotives of those days.

With fuel the major cost of locomotive operation, the railroads may no longer be able to afford the luxury of sole dependence on diesel locomotives, particularly because of technological advancements that enable them to burn coal cleanly and efficiently in a locomotive that is fully compatible with the efficient operating practices that have been developed over the last thirty years. The benefits of coal-fired locomotives versus diesels have been evaluated with respect to several operating scenarios and reported elsewhere in considerable detail, as noted below. For the purpose of these hearings, we wish to summarize the conclusions of those evaluations.

In one such evaluation, the relative cost of operating unit coal trains on a major railroad division serving the western coal regions were estimated. In the first case, the unit coal trains were powered by diesel locomotives; in the second case, the unit coal trains were powered by ACE 3000-8 locomotives. The cost comparison included estimates for all special shops, facilities, and added rolling stock to support the coal-fired ACE locomotives. Figure 3 shows the results of the comparison for yearly fuel and maintenance expense. The reduction in fuel cost is made more dramatic because of assumed availability of coal at the mine-mouth price of $.47 per million BTU. However, even if an average delivered price of $1.35 were used, the yearly fuel bill would drop from $80,000,000 to approximately $27,000,000, a very substantial reduction, which brings fuel cost back to one-quarter of the cost of locomotive ownership. The reduction in yearly maintenance shown in Figure 3 is because fewer ACE 3000-8 locomotives are required than the diesels they replace; the steam locomotive generates considerably more power at intermediate and high speeds than the diesels. In economic terms to the railroad, the initial investment of acquiring coal-fired locomotives and establishing their support structure costs approximately $90,000,000 more than acquiring diesel locomotives for the same service. But this additional investment cost is offset by annual savings of $80,000,000, which will be returned every year as long as the relative price of energy is maintained. The bottom line of the cost comparison is summarized in Table 2.

TABLE 2
THE BOTTOM LINE

Unit coal train scenario:

40 Billion net ton-mile per year
Approximately 6000 unit coal trains
Approximately 200 locomotives

Internal Rate of Return	86% per year
Net Present Value based on constant dollars, 6% discount rate, for a 15-year planning horizon	$673,000,000
Payback Period	1.2 years

In a second evaluation of coal as a rail fuel which we wish to introduce into the record of these hearings, the financial rate of return has been evaluated for six scenarios which were developed by the Federal Railroad Administration in its assessment of railroad electrification (reference: C. H. Spenny, "An Update of the Costs and Benefits of Railroad Electrification", Project Memorandum, US-DOT-FRA-TSC Report No. PM-742-C-14-83, April 8, 1980). Using these scenarios is an expedient which provides a data base substantiated by extensive and detailed engineering cost analyses. Three scenarios were national networks carrying more traffic (gross-ton-miles per mile) than any other network of the same route lengths. The other three scenarios were high traffic density routes, less than 1000 miles long, with site-specific costs developed by A&E firms. Because of their high traffic density, all six scenarios were prime candidates for electrification, which is capital intensive. The deployment of coal-fired steam locomotives is not capital intensive. Thus, the scenarios may not be optimal for coal-fired locomotive operation.

The costs for coal-fired steam motive power were added to the capital and operating costs for electrification versus diesel motive power available from the FRA study. The cost factors are summarized in Table 3. (Investment and operating cost figures for the various scenarios are available in: "Economics of a New Coal-Fired Locomotive", John T. Harding, South and Southwestern Railway Association Proceedings, April 1981, pp. 7-25.) Rates of return on investment (ROR) resulting from annual savings for electrification and for coal-fired locomotives are summarized in Tables 4 and 5. All the ROR assumptions are those of the FRA electrification study. In every scenario, ROR's for the coal-fired steam locomotive are considerably higher than for electrification. Net present values (NPV) have also been calculated. Net present values, net investments, and their ratios, are shown in Table 6 for electric and steam motive power. Coal compares very favorably with electrification. Furthermore, the NPV's for coal are very robust, remaining positive even with considerable increase in investment costs. The conclusion is that modern coal-fired steam locomotives should be considered seriously as an alternative motive power on the nation's railroads.

TABLE 3

ALTERNATIVE MOTIVE POWER COST FACTORS

1980 PRICES

CAPITAL COSTS

	THOUSAND DOLLARS/ROUTE MILE		
	SINGLE TRACK		DOUBLE TRACK
CATENARY	175		318
SUBSTATIONS & BREAKER STATIONS	87		158
SIGNAL & COMMUNICATIONS MODS.	142		210
CIVIL RECONSTRUCTION	54		79
TOTAL	458		765
UTILITY CONNECT COSTS		15	
COAL HANDLING AND WATER TREATMENT FACILITIES		10	

	COST THOUS. $	COST/H.P. $
LOCOMOTIVE COSTS		
DIESEL ELECTRIC	791	264
ELECTRIC (3.8 MW)	1540	302
COAL-FIRED (3000 H.P.)	1250	417

OPERATING COSTS

DIESEL ENERGY	93¢/GAL
ELECTRIC ENERGY	4.23¢/KWH
COAL ENERGY	$48/TON
DIESEL LOCOMOTIVE MAINTENANCE	133¢/UNIT MILE
ELECTRIC LOCOMOTIVE MAINTENANCE	65¢/UNIT MILE
COAL LOCOMOTIVE MAINTENANCE	133¢/UNIT MILE
CATENARY MAINTENACE 2 TRACK	$4400/ROUTE-MI YEAR

TABLE 4

RATE OF RETURN FOR THREE NETWORK SCENARIOS
(PERCENT)

SCENARIO	ELECTRIFICATION		COAL-FIRED STEAM LOCOMOTIVES[a]	
	W/O FUEL DIFFERENTIAL	W/FUEL DIFFERENTIAL[b]	W/O FUEL DIFFERENTIAL	W/FUEL DIFFERENTIAL[b]
10,000 ROUTE MILE NETWORK	15	18	29	35
26,000 ROUTE MILE NETWORK	12	15	28	34
40,000 ROUTE MILE NETWORK	11	14½	27	33

NOTES

1980 Cost Estimates
Assumes 2% Annual Rail Traffic Growth, No General Inflation, 30 year horizon.
a) Assumes Twice As Many 3000 hp Coal-fired Locomotives As 3.8 MW Electric Locos in Each Network
b) Fuel Differential: Diesel Fuel Cost Escalates 3%/y Faster Than Electricity Or Coal

TABLE 5

RATE OF RETURN FOR THREE SITE SPECIFIC SCENARIOS
(PERCENT)

SCENARIO	ELECTRIFICATION		COAL-FIRED STEAM LOCOMOTIVES[a]	
	BASE ROR	WITH FUEL DIFFERENTIAL[b]	BASE ROR	WITH FUEL DIFFERENTIAL[b]
MIXED FREIGHT	19	23	28	34
HIGH SPEED FREIGHT	19	23	33	39
UNIT COAL TRAIN	21½	25	32	37

NOTES

1980 Cost Estimates
Assumes 3.2% Annual Rail Traffic Growth, 5%/y General Inflation
a) 3000 H.P. Coal-fired Locomotives Replace Diesel-electric Units On A 1:1 Basis
b) Fuel Differential: Diesel Fuel Costs Escalate 3%/y Faster Than Electricity Or Coal

TABLE 6

NET PRESENT VALUES OF MOTIVE POWER ALTERNATIVES FOR SIX RAILROAD SCENARIOS

1980 PRICES - $ MILLIONS

SCENARIO

	NATIONAL NETWORKS						SITE SPECIFIC ROUTES					
	10,000 mi.		26,000 mi.		40,000 mi.		Mixed Freight		Hi-Speed Freight		Unit Coal Train	
	ELEC	COAL	ELEC	COAL	ELEC	COAL	ELEC	COAL	ELEC	COAL	ELEC	COAL
INVESTMENT	6740	1910	15,700	3700	22,800	5170	371	124	783	257	154	51
NPV	1725	2898	-155	5274	-1325	7104	41	109	63	346	46.2	62.4
NPV/INV	.26	1.52	-0.1	1.43	-0.6	1.37	.11	.88	.08	1.35	.30	1.22

NOTES

Assumes No Inflation, No Rail Traffic Growth
10% Discount Rate
30 Year Horizon

In the final evaluation of coal as a rail fuel which we wish to identify for the purpose of these hearings, the Jet Propulsion Laboratory studied many alternative fuels and engines for locomotives (reference: "Future Fuels and Engines for Railroad Locomotives", Vol. 1 Summary, Vol. 2 Technical Document, S.G. Liddle et al., JPL Publication 81-101 prepared for U.S. DOE, November 1, 1981). The study resulted in a ranking of locomotives by their annualized life-cycle operating costs in commercial service. Table 7 is taken directly from the JPL Summary volume. The most striking conclusion to be drawn from Table 7 is that if a locomotive burns coal, its annual cost is approximately one-half the annual cost of a standard diesel locomotive of today, or even a significantly improved diesel that may be available several years from now. Furthermore, this comparison is very insensitive to the type of coal-burning locomotive. The most advanced coal-fired engine offered only minor reduction in annual cost with respect to the so-called first generation steam engine (the analysis for which was based on characteristics of the ACE 3000). There is little incentive to spend years of additional development time for only a marginal improvement in yearly operating cost. The most advanced diesel that was considered was an adiabatic turbocompound diesel engine with minimum friction and Rankine bottoming cycle, burning oil-shale distillate fuel and it was still 50% more costly per year than coal-fired locomotives. This research engine is twenty years from practical application to the actual railroad operating environment.

The first generation reciprocating steam engine (the ACE 3000) is based on proven technology and is ready for the final design process culminating within three years in fully operational prototype locomotives on which future production will be based.

TABLE 7

RANKING OF ENGINES BY ANNUALIZED LIFE-CYCLE COSTS

ENGINE	FUEL	ANNUALIZED LIFE-CYCLE COSTS
Closed, cycle, external combustion regenerative gas turbine	Bituminous coal, western mine mouth	$ 523,000
Open cycle, external combustion regenerative gas turbine	Bituminous coal, western mine mouth	527,000
Advanced Stirling engine using liquid fuels	Bituminous coal, western mine mouth	548,000
First generation steam engine with reciprocating drive	Bituminous coal, western mine mouth	549,000
Closed cycle, external combustion regenerative gas turbine	Bituminous coal, national average price	554,00C
Open cycle, external combustion regenerative gas turbine	Bituminous coal, national average price	559,000
Second generation new steam turbine engine	Bituminous coal, western mine mouth	564,000
Advanced Stirling engine using fluidized bed combustor	Bituminous coal, national average price	577,000
Second generation new steam turbine engine	Bituminous coal, national average price	608,000
First generation steam engine with reciprocating drive	Bituminous coal, national average price	615,000
Long-term "mature" Diesel engine	Oil Shale distillate	750,000

TABLE 7 (Cont'd)

ENGINE		
Adiabatic turbocompound Diesel Engine with minimum friction and Rankine bottoming cycle	Oil shale distillate	$ 793,000
Adiabatic turbocompound Diesel with Rankine bottoming cycle	Oil shale distillate	818,000
Adiabatic turbocompound Diesel with minimum friction	Oil shale distillate	840,000
Phosphoric acid fuel cell	Methanol from coal	859,000
Adiabatic Diesel engine with Stirling bottoming cycle	Oil shale distillate	870,000
Advanced Stirling engine using liquid fuels	Oil shale distillate	931,000
Four-stroke turbocharged Diesel engine using directly decomposed methanol	Methanol from coal	940,000
Short-term "mature" Diesel Engine	Broadcut fuel oil	977,000
Open cycle, internal combustion regenerative gas turbine	Oil shale syn-crude	1,029,000
Turbocharged water-cooled Diesel with Rankine bottoming cycle	Diesel No. 2	1,101,000
Phosphoric acid fuel cell	Hydrogen	1,118,000
Turbocharged water-cooled Diesel engine (standard)	Diesel No. 2	1,175,000
Stratified charge rotary combustion engine	Oil shale distillate	1,196,000

2. The ACE 3000 is Based on Proven Technology

Although research and development on coal-fired locomotives in the U.S. largely came to a halt thirty years ago, developments continued elsewhere in the world in order to refine designs, improve efficiency, and increase power-to-weight ratio. A corollary result of improved efficiency was cleaner combustion; fine coal that is discharged as black smoke is a direct loss of energy as well as an unacceptable pollutant. The major improvements in the steam engine occurred in France as a result of the efforts of Andre Chapelon. This work continued in Argentina under Ing. L. Dante Porta, a former student and later colleague of Chapelon. Porta continued improvements in the steam cycle and added improvements to the furnace in the form of a gas-producing combustion system (GPCS) which was suited for a wide range of coal types and qualities, and which eliminated smoke. The GPCS has operated successfully in many locomotives in Argentina (reference: L. D. Porta, "Steam Locomotive Development in Argentina", Journal of the Institution of Locomotive Engineers, London 1959, pp. 205-256). More recently, the GPCS and other steam engine improvements have been transferred to South Africa where steam locomotives are still actively employed in commercial service. The results are impressive. A modern steam locomotive of German design (Henschel, Class "25", No. 3450) was modified following the design principles of Porta. It has been redesignated Class "26" and has been dubbed the "L. D. Porta". It is shown under full power pulling up-hill on the Kimberly-DeAar line, in Figure 4. It's performance, achieved in normal commercial service, has resulted in a 50% power increase, 28% reduction in coal consumption, 30% reduction in water consumption, corresponding to an approximate doubling of locomotive efficiency. The No. 3450 locomotive is an operating demonstration of the combustion and steam engine technology that will be incorporated in ACE 3000 locomotives.

Figure 5 summarizes the physical and operating characteristics of the ACE 3000 locomotive. The GPCS will be augmented by an automatic control system which will also control the steam engine and all other equipment and subsystems of the locomotive. In addition, a bank of multi-cyclone dust collectors will be provided for further clean-up of exhaust gas. The steam engine improvements of the 3450 will be applied to both cylinder pairs in the ACE 3000 in a compound expansion cycle. Exhaust steam will be condensed and recirculated, rather than escape to the atmosphere. This also contributes to higher engine efficiency.

Brief Technical Description

The ACE 3000 locomotive consists of a power unit and a support unit which are drawbar-coupled back-to-back with each unit having a cab in front. The power unit contains the furnace and combustion system, ash collection and storage, gas clean-up and exhaust, boiler and steam generator, steam engine, condenser and control cab. The support unit contains the coal storage area and stoker-screw, water storage, heat transfer assemblies and fans for cooling circulating water, and control cab.

The ACE 3000 is powered by a 4-cylinder reciprocating steam engine incorporating an opposed-piston arrangement that is inherently balanced at all speeds. There are four pairs of drive wheels. The steam expansion cycle is compound. Spent steam is further expanded through a small turbine for auxiliary power, then condensed, cooled on board the support unit and the recovered water is recycled through the boiler and steam generator.

The pistons are designed for a precision fit within easily replaceable cylinder liners. They have multiple rings for low leakage and long wearing life. The cylinders themselves are jacketed with steam to reduce heat loss from the steam cycle and insure a uniform wall temperature that is within the range of available cylinder lubricants. Control valves incorporate improvements which reduce pressure loss.

The gas-producing combustion system (GPCS) was selected for its low carbon loss and favorable environmental characteristics. The gas-producer furnace burns coal in two stages. Coal is mechanically distributed across a thick fuel bed supported on an oscillating shuffle grate. Coal devolatilizes in the fuel bed leaving behind the char component which gasifies. Char gasification is controlled by maintaining air flow up through the fuel bed at less than the amount required for complete combustion and by injection of steam into the air flow. When burned in this fashion, temperature of the burning coal is relatively low, which facilitates agglomeration and collection of the noncombustible ash component of the coal, which in other combustion processes is discharged to the environment. Furnace design minimizes gas velocity through the fuel bed and reduces entrainment of fine particules of ash and coal in the flue gas. Volatile components and char gasification products are burned to completion above the fuel bed. This type of combustion has been employed in steam locomotives in Argentina and South Africa confirming that it is clean and efficient. Ash is agglomerated and collected as a residue; there is no smoke; there is no fouling of heat transfer surfaces in the boiler; and coal burns to completion with very little carbon loss. Because of the reduced combustion temperature in a gas-producing furnace, emission of nitrogen oxides is also very low. Emission of sulfur oxides can be kept within proposed standards by burning low sulfur coal (less than two percent) which is readily available in the quantities required for railroad locomotives.

The firebox chamber is confined within the boiler walls. Boiler steam pressure is normally 300 psi; structural integrity is maintained by staybolts in accordance with well-established locomotive boiler design practice. The firebox transitions into a cylindrical firetube assembly that provides additional surface for raising steam as well as superheat surface. Steam collected from the top of the boiler drum passes through superheater tubes that loop into the firetubes and then passes to the throttle and high pressure cylinders.

The ACE 3000 will have a condensing steam cycle. This greatly reduces requirements for make-up water and eliminates the need for new watering facilities. Water introduced into the boiler is treated to control dissolved solids and chemical impurities, eliminating waterside corrosion and scale formation in the boiler. The condensing cycle improves engine efficiency by reducing back pressure, and enables the locomotive to derive more cylinder power from the same quantity of steam.

In order for the ACE 3000 to operate in multiple unit with other ACE 3000's or with diesels, it will be equipped with a computer control system implemented with microprocessor-based hardware. The control system will respond to the operator's throttle and braking commands in accordance with speed, load, and emission control requirements.

The ACE 3000 is a new locomotive for a new era. It incorporates innovations in combustion, engine design, and locomotive control, each of which have been demonstrated in railroad or other related applications. The innovative aspects of the design and its unique configuration distinguish it from previous locomotives insuring clean, efficient, reliable, and low maintenance operation that is entirely compatible with current railroad operating practice. American Coal Enterprises has the people and experience to proceed immediately with final design of prototype locomotives. The technology is available now, with no further development delays.

3. New Market Potential for Coal

Figure 6 illustrates coal consumption since 1950, and includes DOE's projection through 1990. Coal used for transportation amounted to approximately 60 million tons per year in 1950 (9% of the total), and decreased steadily after that as coal-fired locomotives were phased out. If coal is reintroduced as a rail fuel, its relative effect on total coal consumption will now be smaller. However, a new customer for several million tons of coal per year can have beneficial local effects in mining regions such as Virginia where production is well below capacity and the coal is relatively low in sulfur.

A more accurate estimate of potential new coal requirements for rail transportation can be based on current fuel consumption by locomotives. In 1982, U.S. railroads consumed 3,163,486,000 gallons of diesel fuel, with an energy equivalent of 0.437×10^{15} BTU. If all diesels were converted to coal locomotives at approximately one-half the efficiency of a diesel, twice as much energy would be required corresponding to 34,000,000 standard tons of coal per year. Replacement of about half the existing fleet is not unreasonable within a decade, which implies a potential new market approaching 20,000,000 tons per year.

4. Coal-Fired Steam Locomotives Can Be Cleaner Than Diesels

The standard for diesel locomotive emissions relates to darkness of the exhaust. "No. 2" on the Ringlemann Chart is the requirement for normal operation (excluding starting, accelerating, etc.) between sea level and 5000 ft., which corresponds to 40% opacity (No. 3 Ringlemann, and 50% opacity above 5000 ft.). In emission tests of a Southern Pacific diesel locomotive, typical emissions under sustained operation at or near full power were:

Carbon monoxide	200 to 400 parts per million (ppm)
Hydrocarbons	1100 ppm
Nitrogen oxides	1000 ppm

The ACE 3000 locomotive will have no carbon monoxide emission, no hydrocarbon emission, much lower nitrogen oxides emission, and 10% opacity (which is typical of the performance of GPCS locomotives in Argentina and South Africa).

Sulfur dioxide emission will be approximately the same as diesels (Reference: M. Dayne Aldridge, et al., "Coal as a Rail Fuel: An Assessment of Direct Combustion", West Virginia University Energy Research Center, Morgantown, August 15, 1980). However, there is an important difference in character between the sulfur dioxide emissions from diesels and from coal-fired steam locomotives. The sulfur dioxide from diesels exists in the presence of the unburned hydrocarbon emissions, which constitute an oil-soot. The oil-soot contains the impurities of the unburned fuel, which are effective catalysts in the conversion of sulfur dioxide to acid rain. Typically these impurities are metallic elements present in differing quantities depending on the source of oil. These impurities are not found in coal.

The pathways by which sulfur dioxide is converted to acid rain are complex, and involve time, mixing and dispersion phenomena, and catalytic agents. It appears that sulfur dioxide produced by internal combustion engines converts rapidly to acid rain because of the presence of catalysts in the fuel, whereas the sulfur dioxide from coal converts much more slowly and mixes more effectively with the natural background. (Reference: Professor A. M. Squires, Virginia Polytechnic Institute and State University, Department of Chemical Engineering, Blacksburg, Virginia.) This is certainly an area worthy of more study and investigation.

Average Energy Cost Comparison

Coal and Diesel Fuel

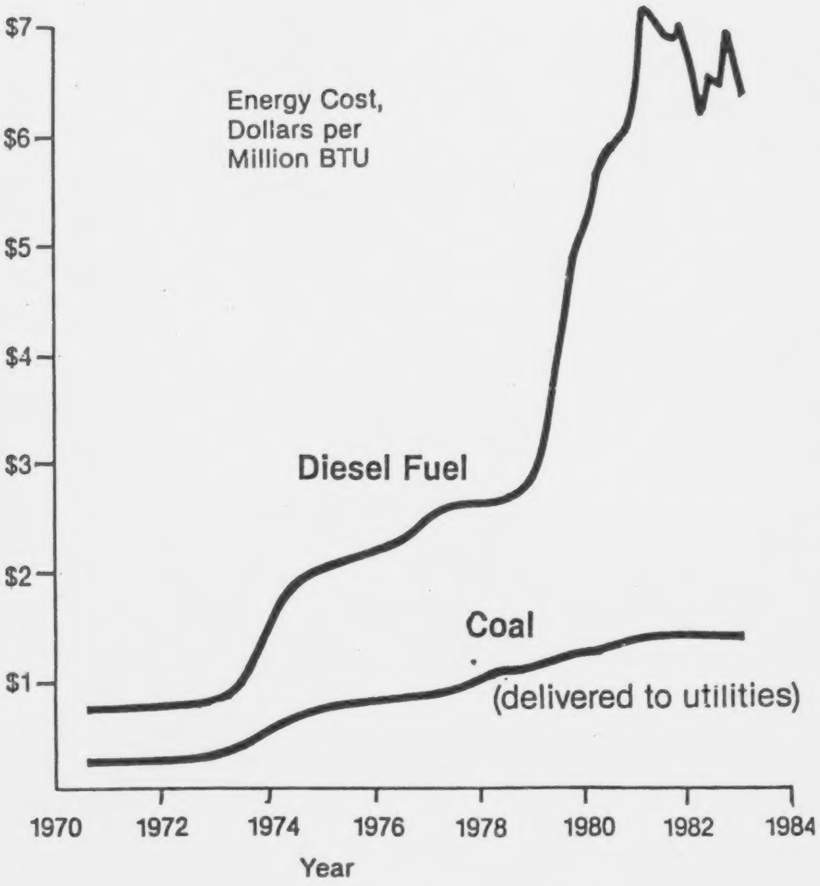


FIGURE 1

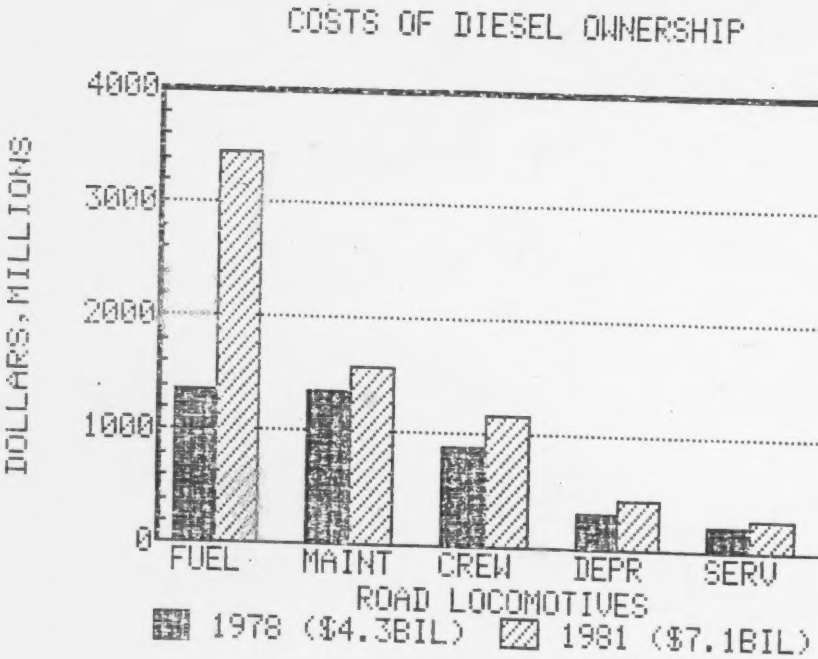

COSTS OF DIESEL OWNERSHIP
DOLLARS,MILLIONS
4000
3000
2000
1000
0
FUEL
MAINT
CREW
DEPR
SERV
ROAD LOCOMOTIVES
1978 ($4.3BIL)
1981 ($7.1BIL)

FIGURE 2

ACE 3000-8's Will Reduce Unit Coal Train Operating Costs

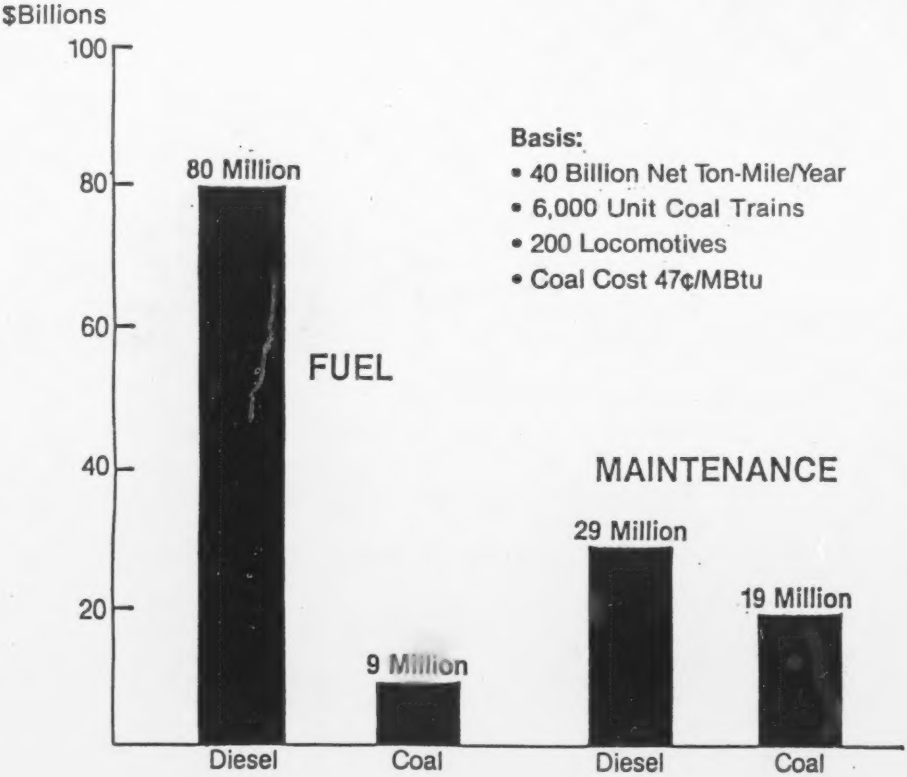
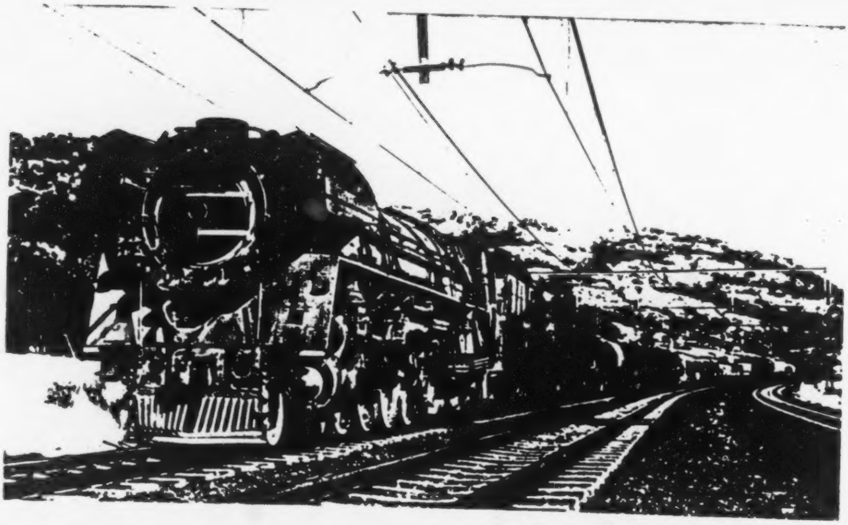


FIGURE 3

South African Railways

Class 25 Locomotive, No. 3450, "The L. D. Porta"



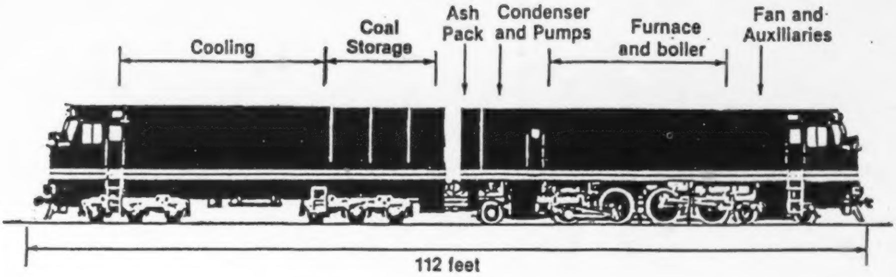
Performance improvement achieved in normal service:

- 50% increase in power
- 28% decrease in coal consumption
- 30% decrease in water consumption
- Approximate doubling of overall efficiency

ACE 3000 Combustion and Steam Engine Technology is in Commercial Service, Today.

FIGURE 4

ACE 3000-4 Coal-Fired Steam Locomotive

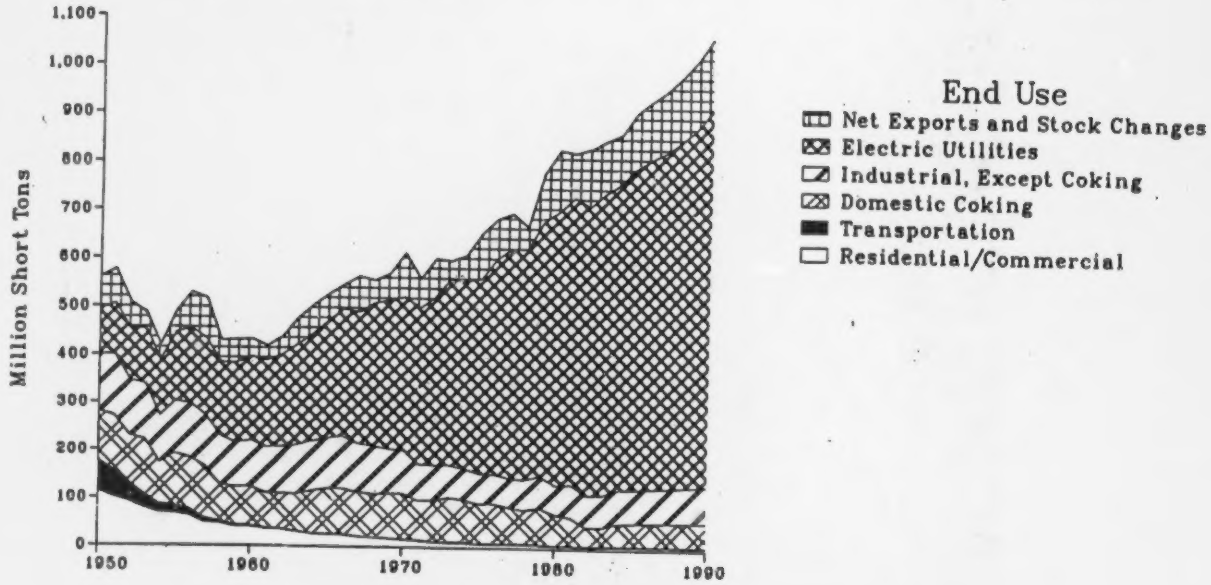


Operating Characteristics

- Unrestricted bidirectionality
- 15 hour range, continuous operation, full power
- Condensing steam cycle
- Clean exhaust
- 4-cylinder compound expansion engine
- Dynamically balanced, interconnected drive
- Computer control
- MU capable with ACE 3000 or with diesel
- Fits railroad clearances on 100% of U.S. track mileage
- Continuous tractive effort 70,000 lb. 0 to 20 mph
- Drawbar Horsepower 4,000 hp, 20 to 80 mph

FIGURE 5

Coal Consumption by End Use, Midprice Scenario, 1950 to 1990
(Million Short Tons)



Source: Historical data: Energy Information Administration, 1981 Annual Report to Congress, Volume 2, DOE/EIA-0173(81)/2 (Washington, D.C., 1982), Monthly Energy Review, DOE/EIA-0035(83/2) (Washington, D.C., 1983), and Weekly Coal Production, DOE/EIA-0218, selected issues.

FIGURE 6

BRIEFING CHARTS

TESTIMONY BEFORE FIELD HEARINGS

Senator John Warner

REINTRODUCTION OF COAL AS A FUEL FOR RAIL TRANSPORTATION

American Coal Enterprises Inc.
2185 Dow Drive
Akron, OH 44313

November 28, 1983

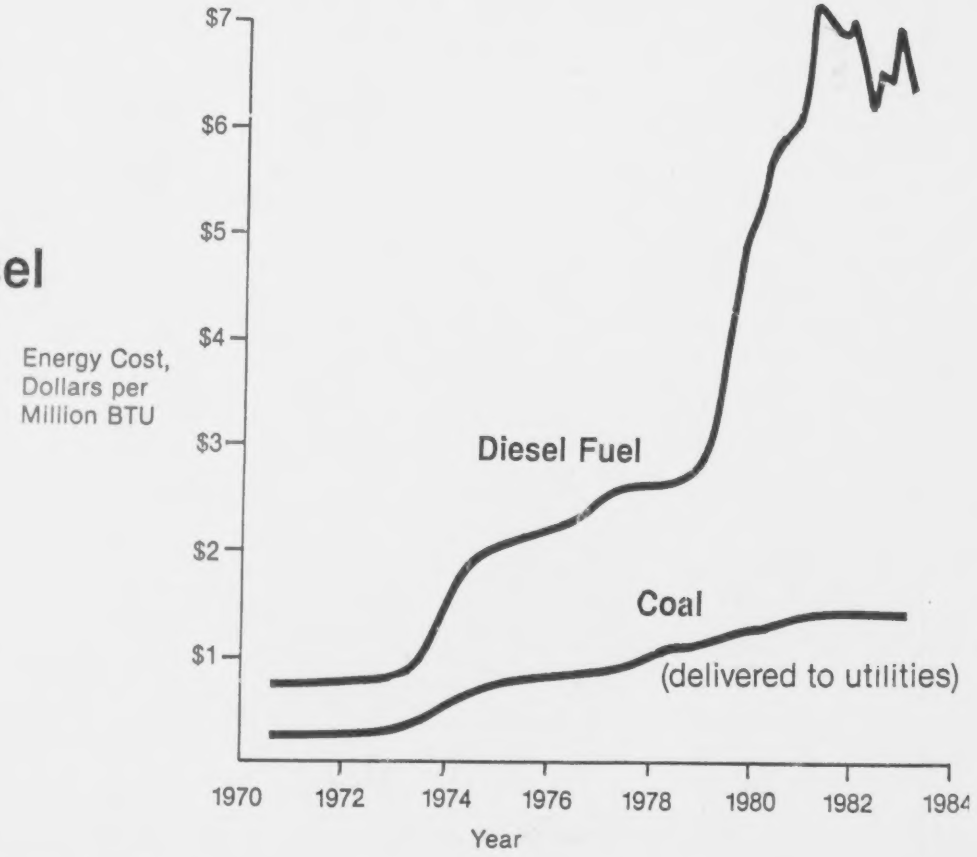
Roanoke, Virginia.

ACE 3000 COAL-FIRED LOCOMOTIVE

1. MAJOR REDUCTION IN RAILROAD FUEL COST;
   GREAT SAVINGS TO THE RAILROADS
2. LOW TECHNOLOGICAL RISK;
   BASED ON PROVEN TECHNOLOGY
3. SIGNIFICANT NEW MARKET FOR VIRGINIA COAL
4. WILL IMPROVE ACID RAIN SITUATION

Average Energy Cost Comparison

Coal and Diesel Fuel



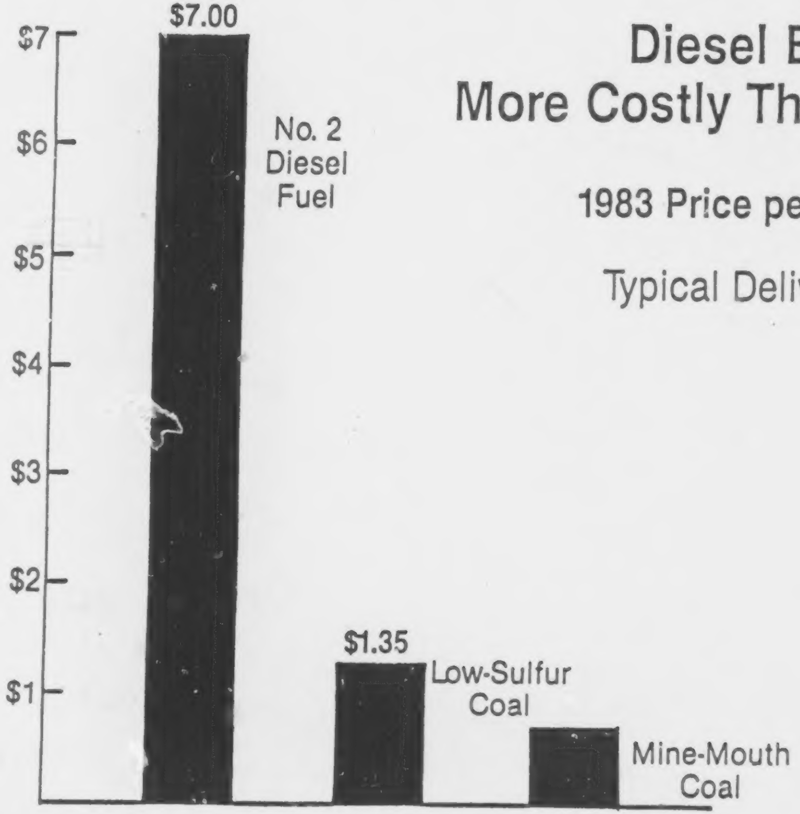
Source: D.O.E.: EIA 1983

UNIT COAL TRAIN SCENARIO

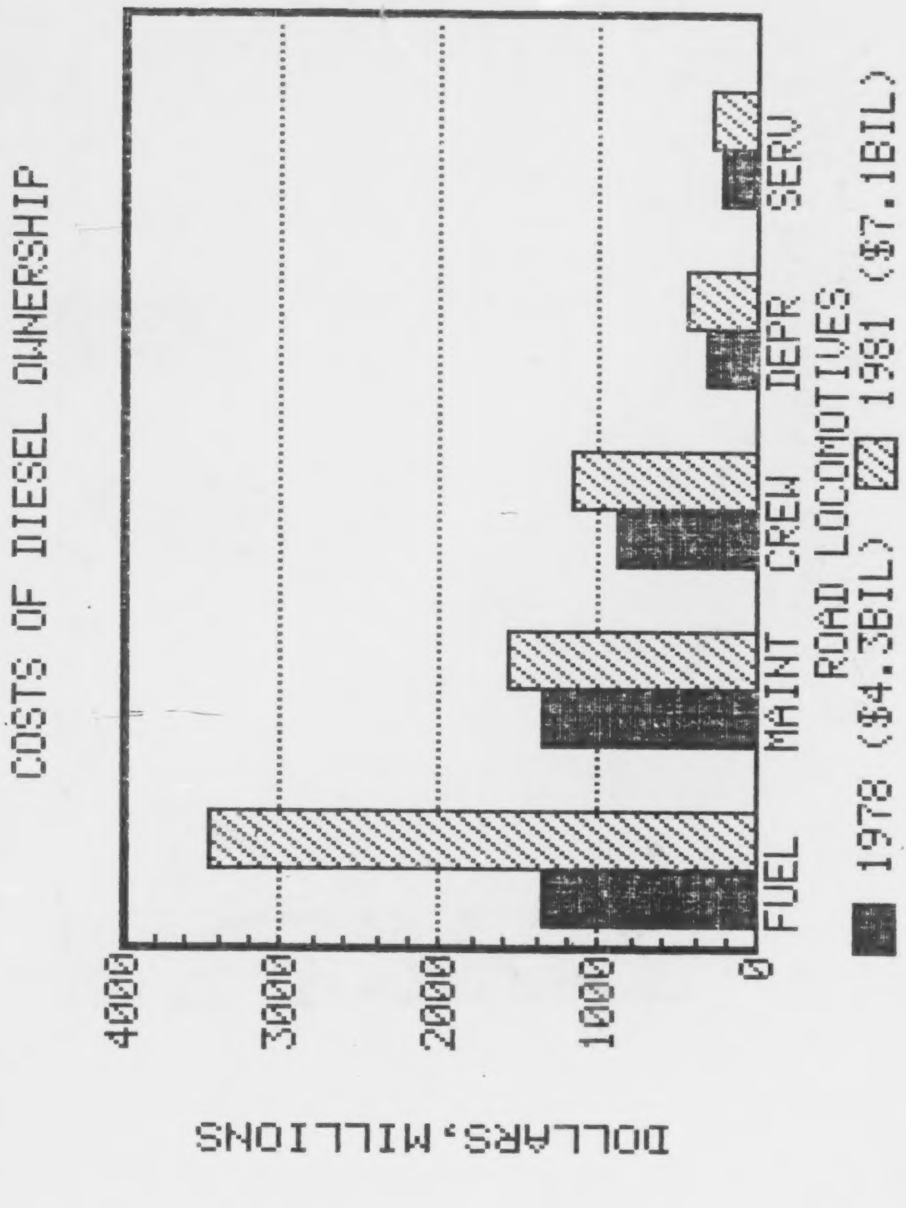
Diesel Energy is More Costly Than Coal Energy:

1983 Price per Million BTU

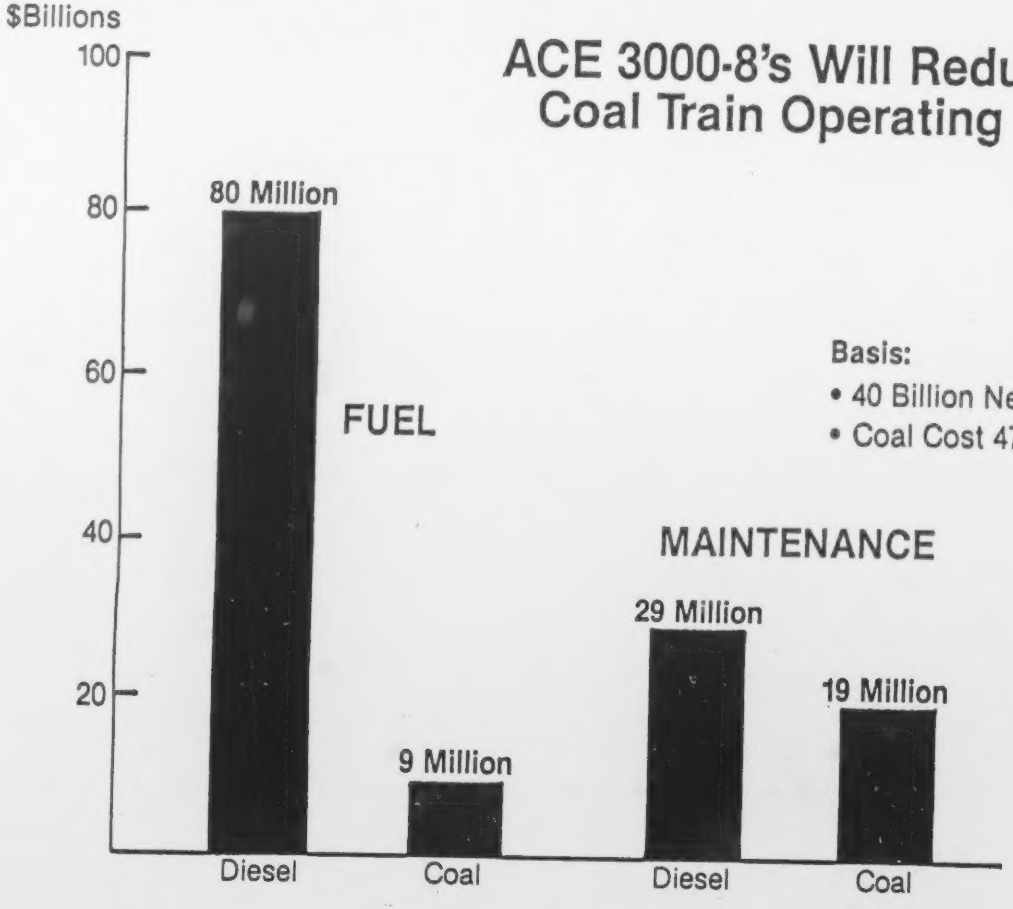
Typical Delivered Prices



Source: D.O.E.: EIA 1983

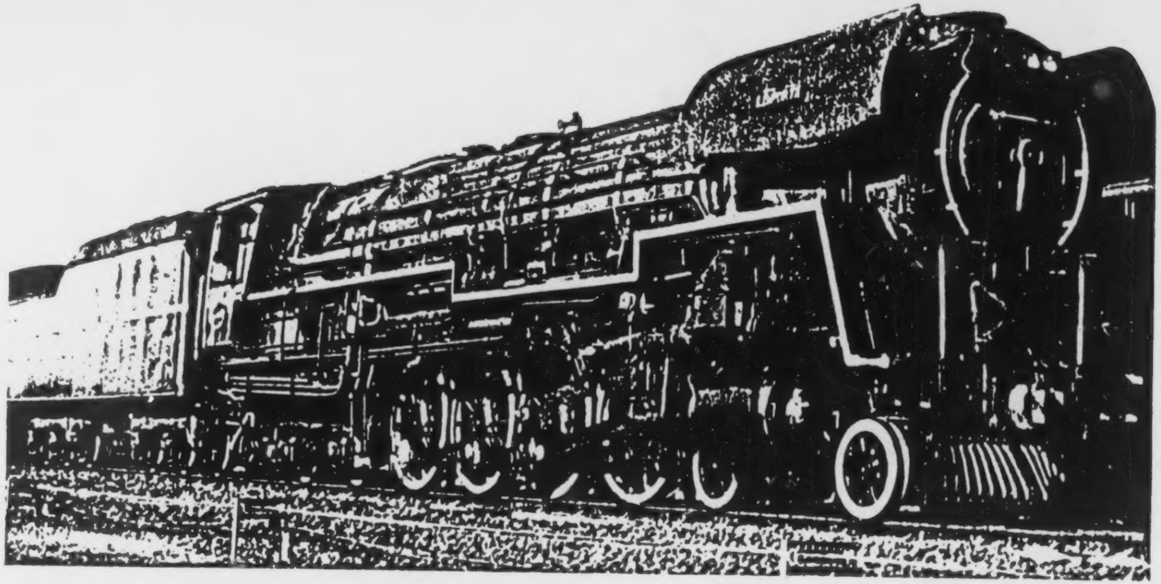

COSTS OF DIESEL OWNERSHIP
DOLLARS, MILLIONS
4000
3000
2000
1000
0
FUEL
MAINT
CREW
DEPR
SERV
ROAD LOCOMOTIVES
1978 ($4.3BIL)
1981 ($7.1BIL)

ACE 3000-8's Will Reduce Unit Coal Train Operating Costs



Basis:

- 40 Billion Net Ton-Mile/Year
- Coal Cost 47¢/MBtu



CLASS "26" LOCOMOTIVE No. 3450

CURRENTLY IN COMMERCIAL SERVICE

50% INCREASE IN POWER; 28% REDUCTION IN COAL CONSUMPTION

APPROXIMATE DOUBLING OF LOCOMOTIVE EFFICIENCY

OPERATING DEMONSTRATION OF COMBUSTION AND STEAM ENGINE TECHNOLOGY THAT WILL BE INCORPORATED IN ACE 3000 LOCOMOTIVES

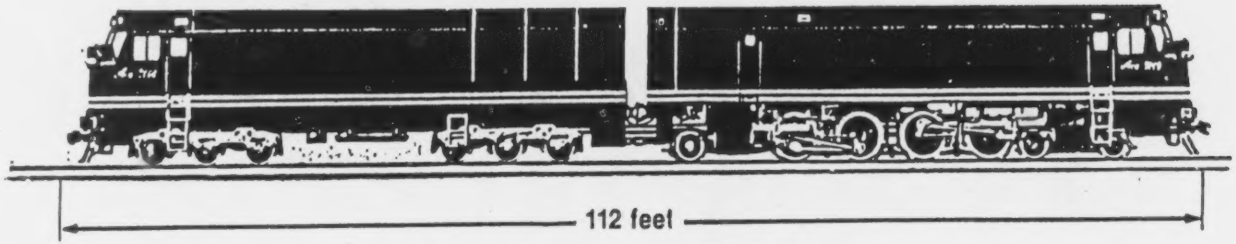
40 BILLION NET TON-MILE/YEAR
6000 UNIT COAL TRAINS
200 LOCOMOTIVES

THE BOTTOM LINE (before taxes)

PAYBACK PERIOD	1.2 YEARS
INTERNAL RATE OF RETURN	86%/YEAR
NET PRESENT VALUE 6%/year Constant dollars 15 year horizon	$673 MILLION
PROFITABILITY INDEX	7.4

ACE 3000-4 Coal-Fired Steam Locomotive

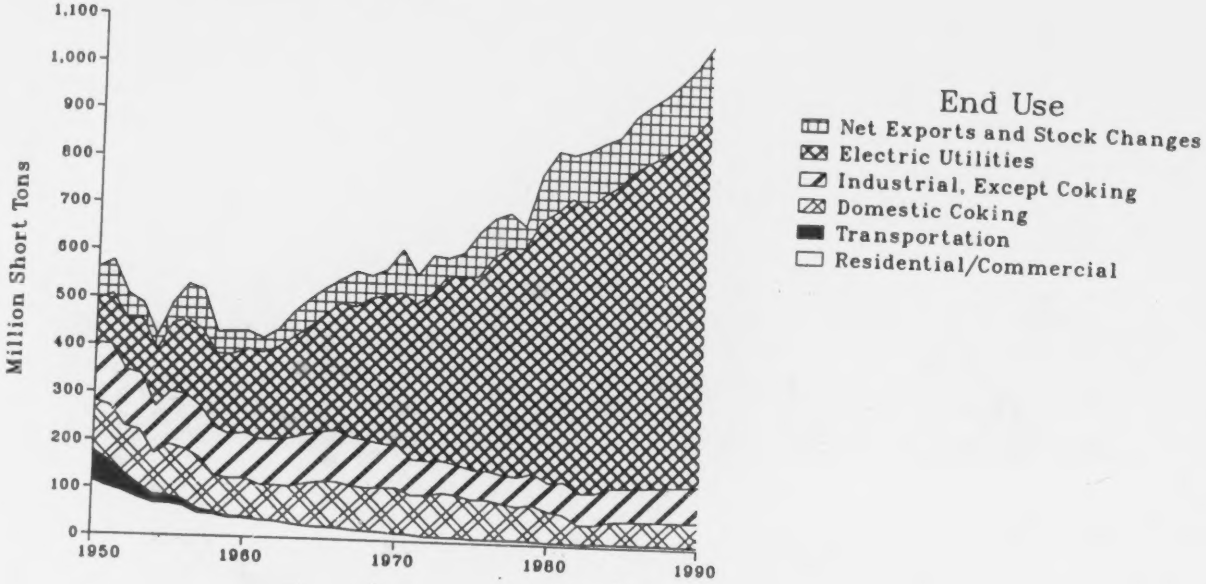
Continuous tractive effort	70,000 lb. 0 to 20 mph
Drawbar Horsepower	4,000 hp. 20 to 80 mph



Operating Characteristics

- Unrestricted bidirectionality
- 15 hour range, continuous operation, full power
- Condensing steam cycle
- Clean exhaust
- Computer control
- MU capable with ACE 3000 or with diesel
- Fits railroad clearances on 100% of U.S. track mileage

Coal Consumption by End Use, Midprice
Scenario, 1950 to 1990
(Million Short Tons)



Source: Historical data: Energy Information Administration, 1981 Annual Report to Congress, Volume 2, DOE/EIA-0173(81)/2 (Washington, D.C., 1982), Monthly Energy Review, DOE/EIA-0035(83/2) (Washington, D.C., 1983), and Weekly Coal Production, DOE/EIA-0218, selected issues.

1982 FUEL CONSUMPTION BY U.S. RAILROADS

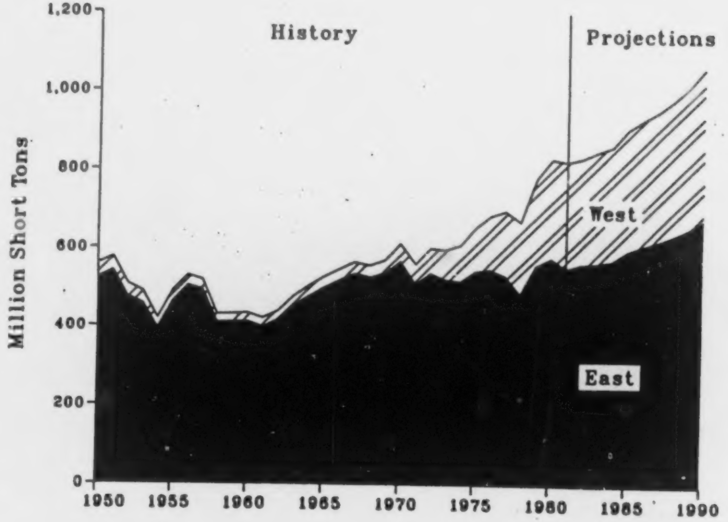
Source: Association of American Railroads
Economics and Finance Department

3,163,486,000 gallons diesel fuel
Average price $0.95/gallon
Energy equivalent 0.437×10^{15} BTU

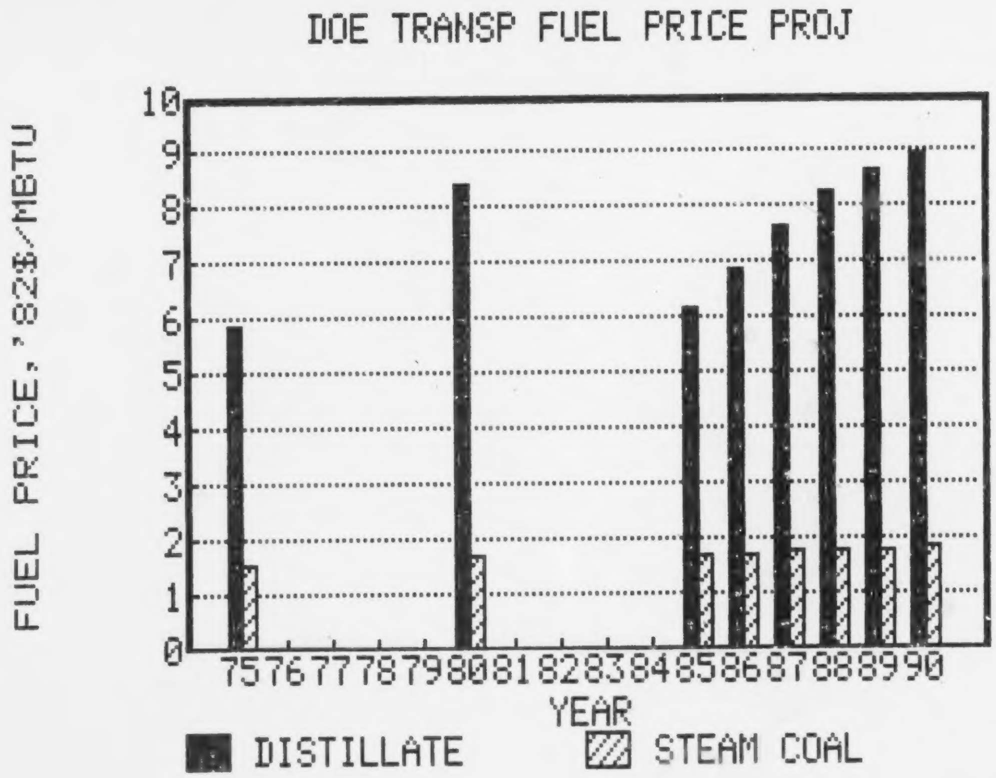
IF ALL LOCOMOTIVES BURNED COAL AT ONE-HALF THE EFFICIENCY OF A MODERN DIESEL LOCOMOTIVE, THEN

Coal equivalent is 0.873×10^{15} BTU, or
34,000,000 standard tons/year

Coal Production by Major Producing Region,
Midprice Scenario, 1950 to 1990
(Million Short Tons)



Source: Historical data: U.S. Department of the Interior, Bureau of Mines, Minerals Yearbooks, (Washington, D.C.) selected years; Energy Information Administration, 1981 Annual Report to Congress, Volume 2, DOE/EIA-0173/(81)/2 (Washington, D.C., 1982) and Weekly Coal Production, DOE/EIA-0218, selected issues.



Source: 1982 Annual Energy Outlook with Projections to 1990, Energy Information Administration, April 1983

ACE 3000 IS ENVIRONMENTALLY ACCEPTABLE

CLEANER THAN DIESEL LOCOMOTIVES (NO OIL-SOOT)

NO_X LOWER THAN DIESELS

SO_2 APPROXIMATELY THE SAME AS DIESELS

Reference: West Virginia University, Energy Research Center
"Coal as a Rail Fuel", 1980

SIGNIFICANT REDUCTION IN ACID RAIN DEPOSITION

ACE 3000 exhaust is free of impurities present in oil-soot that catalyze conversion of SO_2 to acid rain.

Reference: Professor A. M. Squires
Virginia Polytechnic Institute and State University
Blacksburg

Senator WARNER. Now, what do you mean when you say conventional?

Mr. ROWLAND. This is first generation, as we know in this country.

Senator WARNER. This is the most modern or one of the most modern versions?

Mr. ROWLAND. Yes, sir. Let me try to say this in steam terms so everybody can understand it. One of the crucial pieces of the ACE3000 locomotive is the new furnace or firebox which we say will triple the thermal efficiency from the old days to the new. This locomotive has recently, courtesy of the South African railways, been retrofited with Dante's fire-box design which we intend to use in our engine and have received, by the way, U.S. patent on. This locomotive versus 24 of its sister locomotives—and they are in every day service—was retrofited with Dante's ideas, machinery, and put back in service. The results have been even more dramatic than he claimed they would be. Basically, the locomotive now produces 50 percent more power than it used to and has reduced its fuel consumption by 25 percent and its water consumption by 30 percent. So, for the same buck you've got basically twice the horsepower. And keep in mind, please, that this was done within the constraints of an existing locomotive without the advantages we'll have in the ACE engine of starting from scratch. He had to hide and cram things here and there, wherever he could get them. The South African railways have been so impressed with the results of this test locomotive that they have decided to retrofit 10 more immediately and if the results from the 10 more are as impressive as the results from the single locomotive, it's our opinion that they'll retrofit the entire fleet.

Senator WARNER. Is that one of the last of the old steam fleets in the world?

Mr. ROWLAND. No sir. There are today in the free world very few countries, South Africa being one of them, which still run steam. In the central economy, in the Communist world, the Chinese run 12,000 steam engines every day and the Russians run about 8,000 every day. And we think, by the way, as an aside that they are prime customers for this retrofit.

Again, another diagram that shows you the characteristics of our locomotive unrestricted bidirectionality, 15 hour range, continuous operation at full power. A condensing steam cycle which allows you to reuse the water. And, more important, allows you to clean the boiler which is a major maintenance item in the old locomotive once a year instead of once a month by controlling the quality of the water that you put into it. Because it does not exhaust to atmosphere that condenses the water, we are able through the gas producer combuster furnace and the induced draft fan too, we feel and we've tested this every which way we can in the computer—we believe this locomotive will be cleaner than the present day diesel electrics running right now. With run-of-the-mine coal. As long as the sulfur content of the coal does not exceed 1.5 percent which fortunately, for instance, in Virginia—most of the soft coal in Virginia is well under that.

The microprocessor will play an important part in this locomotive. Why? Because to be attractive to the railroads the engine has to be able to be operated in multiple unit situations where there are five, six, or seven locomotives hooked together run by one engineer in the front engine. So all the commands have to be electrical in nature and the firing of the locomotive, et cetera, et cetera, has to be automated. We are fortunate to have on our staff the gentleman who was in charge of the project for the Norfolk and Western in the 1950's when they built the John Henry, which is the engine Mr. Scott testified on. And that was a fully automated firing system on that engine. Very much like the one that we use on this engine.

This is a little flow diagram that shows in the blue the steam and water cycle. And in the orange and red the coal combuster cycle and the dust cycle.

Let me introduce, if I may, Dr. David Berkowitz, who is our senior vice president in engineering. David, do you want to for just a minute come up here and explain the two cycles, very briefly?

Dr. **Berkowitz**. This is the power unit. The support unit is to the left. And there's lump coal that is pulled into the screw and mechanically distributed across the firebed. It's a pitfire bed that gasifies into temperatures in the same range that was mentioned by Fred Prahl, 1,700 degrees or so. It's cooled and the ash is collected. The ash is not entrained. Most of the combustion occurs in the space above the firebed. That's where the intense flame is. And the heat transfer and boiling occurs in this region economizing that region. And the furnace draft is controlled by a fan. The combustion system is much more precisely controlled than in the conventional steam locomotive. And there is little loss of carbon, of coal from the firebed, and little loss of ash which is fully retained in the combustion furnace. The fact that this locomotive burns all the coal instead of sending half of it up the smokestack inherently gives it a 50-percent increase in its efficiency. Improvements on the steam side of things. Use of a compound steam expansion cycle, streamlining of the all the internal steam pathways, so that the energy in the steam is used to make the locomotive go instead of pushing steam through passages and around corners. These are some of the innovations that have been incorporated in locomotives in South Africa and Argentina which enable the overall efficiency of the locomotives to be three times what the conventional steam locomotives were.

Mr. **Rowland**. Thank you, David. That's about it, Senator.

Senator **Warner**. Would you say that essentially your locomotive is taking a state-of-the-art combustion system and heat transfer systems and merely rebuilding the old fashioned steam engine? Is that an oversimplification?

Mr. **Rowland**. It's very close. We have tried, to the extent possible, to use proven technology and to reduce to the extent possible therefore, the technological innovation and risk wherever we could. The reciprocating steam engine, as we are all aware, served this country and the world very well for a hundred years. We built this country with them. We've made some refinements on it thanks to the lessons we've learned in the last 4 years in such areas as lubrication, materials. We can build, for instance, a connecting rod today that's one-tenth the weight of a connecting rod 30 years ago and just as strong. So we've tried to incorporate in all those many areas the lessons we've learned. Computer control technology, for instance. The firing system on this locomotive will be an advancement of the one that worked very successfully on the N&W engine in the 1950's. The bottom line being to keep it simple and keep it running. That's the bottom line. A lot of these other schemes that are very complicated, that involve intricate moving interrelated parts, et cetera, in our opinion will not successfully survive in the extremely hostile, dirty, rough, real world of railroad. I mean, they look good on paper but I don't think they're going to make it in the real world.

Senator **WARNER**. I'm not going to able to judge that. That's a conclusion that has to be reached by others. But in summary of today's hearing, this is the impressions that are left with me. You've got the users of America's rail system beginning to provide impetus to yourself, comparable companies in R&D like a few that we've had here today and, indeed, the two major manufacturers, to take a look at what's out there.

Mr. **ROWLAND**. Well, let's be honest, if I may interrupt your statement, Senator. With all respect to the two major manufacturers, I think the record would show that their interest did not come internally, it came as a result of the interest of their customers who said, "Hey listen (you know) if there's another interruption in oil, you guys better have something in your back pocket to bail us out of this thing." That's how it started.

Senator **WARNER**. Right. We see this confluence currently of interest, research and development, requirements, national defense, the risks with importing oil into this country, all of them coming to bear on this really being an exciting option for America to begin to conserve some of its own domestic fuel as well as reduce the OPEC and other imported fuels. But we're at that juncture where no one is ready to put the capital on the line and move.

Mr. **ROWLAND**. No, that's not it actually.

Senator **WARNER**. Well, let me finish my statement and then you can take the stand. In any event, there are gentlemen who have testified today that they are looking for financing and other incentives to build a prototype. What I'm beginning to perceive is the need for some type of Federal program to work in partnership with the Federal sector to give that measure of—should we say impetus or reassurance, or something—to take this thing another step forward in the prototype cycle. I mean, I've worked in oil shale and the research and development money we've put into oil shale is mountainous. Tons of it. I've been looking at other parallel things with R&D money and all of a sudden I see something that, in my humble judgment, is pretty close to really beginning to return some dividends to the United States. I'm impressed with what I've learned today.

So when I depart here and return, I'm going to begin to see what I can do to get somebody to lay out a public program. And then perhaps come back to you and say now here's the embryo. But let's critique it and then its up to me to see if I can get it through Congress. You were about to make a statement?

Mr. **ROWLAND**. No, I think you've hit it on the head. We have spent $2 million in 2 years. From the time we finished the conceptual engineering of this locomotive. And did all the computer testing on the economic, et cetera. We've spent 2 years trying to find the initiative within the industry to be willing to stand up and say, "Hey, we owe it to ourselves." I mean $35 million to build a prototype and get it on the rails for 9 months and really test the hell out of it. We found, fortunately, one major carrier——

Senator **Warner**. Well, I think the particulars of your company are a private matter.

Mr. **Rowland**. You're right. But I'm trying to say, Senator, I think you're right in the sense that, as someone put it earlier, the industry we're dealing with here is traditionally very conservative. They're not risk takers. So any Federal initiative that would help this and other projects have a chance of proving or disproving themselves, would be a great service to the country, I believe.

Senator **Warner**. Do your colleagues have any questions?

I wonder if I could, just with you seated there, ask one additional question of Mr. Thomas. And that is, was your system looked at by JPL? I've got a JPL report here but I have not had the opportunity to go through it completely.

Mr. **Thomas**. No, Senator, it wasn't. We are relatively new to this technology and this particular approach and the JPL report came out before.

Senator **Warner**. I see. Mr. Prahl, what about your's?

Mr. **Prahl**. The director of that study is aware of our system. I've talked to him. He knows about it. But the concept wasn't in place when they finished that report.

Senator **Warner**. Now, to all three witnesses who've testified about specific systems, do any of you know of other companies doing work with a comparable intensity and determination that your three firms are addressing this problem? In other words, at a subsequent hearing I would want to allow an opportunity for anyone else in the United States who is directing their energies to this problem to be a part of this hearing.

Mr. **Rowland**. I am not aware of any others. In fact, I learned of two more today that I wasn't aware of. [Laughing.]

Senator **Warner**. Well, ladies and gentlemen, I want to say that this has been I think one of the better hearings I've had in 5 years in the Senate and I leave here extraordinarily heartened. I can tell you that in candor. In total candor, I'm excited about this. And the various members of this audience and witnesses who've helped me to get the interest, I want to again express my appreciation to you. There are several persons present today and others who have given me the incentive to really drive on this problem. This is a challenge and I'm going to see if I can't crack it. I want to express my appeciation to my two colleagues, Mr. Sindelar and Ms. Magill, for attending the hearing. I thank you all very much. The hearing is recessed.

[Whereupon, the hearing was recessed, to reconvene Tuesday, December 20, 1983.]

COAL USE BY THE NATION'S RAILROADS

TUESDAY, DECEMBER 20, 1983

U.S. Senate,
Subcommittee on Energy and Mineral Resources,
Committee on Energy and Natural Resources,
Washington, DC.

The subcommittee met, pursuant to notice, at 10 a.m., in room SD-366, Dirksen Office Building, Hon. John W. Warner presiding.

Present: Senator Warner.

Also present: Roger Sindelar, counsel; and Linda Mason, professional staff member for the minority.

OPENING STATEMENT OF HON. JOHN W. WARNER, A U.S. SENATOR FROM THE STATE OF VIRGINIA

Senator **Warner**. The Senate Subcommittee on Energy and Mineral Resources convenes this morning for the second in a series of three hearings on the potential for reintroduction of coal as a fuel for railroad locomotives.

The third hearing will be Monday, January 9 at 10 a.m. in Richmond, VA. Witnesses at the first hearing on November 12 in Roanoke advised me that in approximately 5 years the United States could be burning a fuel in diesel-type locomotives primarily derived from coal. I have accepted this challenge as a very high priority and intend to pursue it until either coal is being burned in rail locomotives, or I am convinced that it simply is not feasible. We all have an obligation to the thousands of unemployed coal miners and railroad workers not to raise false hopes, but to pursue diligently this new technology so that we can accurately and economically assess its feasibility.

The subcommittee is seeking additional testimony on several aspects of burning coal in locomotives: the current status of research and demonstration projects; the outlook for this new technology; drawbacks and problems with coal-burning locomotives; and what, if any, is the appropriate role of the Federal Government in encouraging railroad locomotives to burn coal once again.

Today, some 40,000 U.S. railroad locomotives burn approximately 800,000 gallons of diesel fuel daily. That translates into 4 billion gallons of diesel fuel annually. This puts America's rail fuel bill at approximately $4 billion, since diesel is around $1 per gallon.

So the race is on. There is a big challenge out there to see what we can do to cut back on the need for foreign oil and make America more energy independent, and see what we can do to reduce the cost of powering America's locomotives. We have estimates at the last hearing—cost estimates—which show that perhaps the fuel bill could be reduced by as much as 50 percent if we went to a fuel derived from coal as opposed to the present diesel oil.

This means competitive transportation rates because of the lower costs, and it would enable the rail industry to be more competitive, particularly in the exporting of coal.

Railroads are the lifeblood of our economy, transporting vital goods to every corner of the United States. In times of national emergency, the United States is even more dependent on our railroad transportation system.

In 1981, diesel fuel burned by rail represented 12.4 percent total U.S. consumption of OPEC oil. Because of the possibility of interruption of foreign oil supplies during national emergencies, the dependence of our national rail system on imports of OPEC oil must be removed. The burning of coal by locomotives would reduce oil imports and release available supplies of diesel fuel for other national needs. This is vitally important to our Nation's economy, and vitally important to our overall national defense.

[The prepared statement of Senator Warner follows:]

STATEMENT OF SENATOR JOHN W. WARNER
SUBCOMMITTEE ON ENERGY AND MINERAL RESOURCES
"REINTRODUCTION OF COAL AS FUEL FOR RAILROAD LOCOMOTIVES"
DECEMBER 20, 1983
ROOM SD-366, 10 A.M.

THE SENATE SUBCOMMITTEE ON ENERGY AND MINERAL RESOURCES CONVENES THIS MORNING FOR THE SECOND IN A SERIES OF HEARINGS ON THE POTENTIAL FOR REINTRODUCTION OF COAL AS FUEL FOR RAILROAD LOCOMOTIVES.

THE THIRD HEARING WILL BE MONDAY, JANUARY 9 AT 10:00 A.M. IN RICHMOND, VIRGINIA IN HEARING ROOM "C" OF THE STATE CAPITOL. I ENCOURAGE ALL WHO ARE INTERESTED IN TESTIFYING TO CONTACT THE SUBCOMMITTEE STAFF AS SOON AS POSSIBLE.

WITNESSES AT THE NOVEMBER 12 HEARING IN ROANOKE TOLD ME THAT IN APPROXIMATELY FIVE YEARS THE U.S. COULD BE BURNING COAL IN RAILROAD LOCOMOTIVES. I HAVE ACCEPTED THIS AS A HIGH PRIORITY AND INTEND TO PURSUE IT UNTIL EITHER COAL IS BEING BURNED IN RAILROAD LOCOMOTIVES OR I AM CONVINCED THAT IT SIMPLY IS NOT FEASIBLE. WE ALL HAVE AN OBLIGATION TO THE THOUSANDS OF UNEMPLOYED COAL MINERS AND RAILROAD WORKERS NOT TO RAISE FALSE HOPES, BUT TO PURSUE DILIGENTLY THIS NEW TECHNOLOGY SO THAT WE CAN ACCURATELY ASSESS ITS TRUE POTENTIAL.

THE SUBCOMMITTEE IS SEEKING ADDITIONAL TESTIMONY ON SEVERAL ASPECTS OF BURING COAL IN LOCOMOTIVES: THE CURRENT STATUS OF RESEARCH AND DEMONSTRATION PROJECTS; THE OUTLOOK FOR THIS NEW TECHNOLOGY; DRAWBACKS AND PROBLEMS WITH COAL-BURNING LOCOMOTIVES; AND WHAT, IF ANY, IS THE APPROPRIATE ROLE OF THE FEDERAL GOVERNMENT IN ENCOURAGING RAILROAD LOCOMOTIVES TO BURN COAL ONCE AGAIN.

TODAY, SOME 40,000 U.S. RAILROAD LOCOMOTIVES BURN APPROXIMATELY 800,000 GALLONS DAILY OR FOUR BILLION GALLONS ANNUALLY, OF DIESEL FUEL. WITH DIESEL FUEL COSTING AROUND $1 A GALLON, THIS PUTS AMERICA'S RAIL FUEL BILL AT NEARLY $4 BILLION. THE RACE IS ON, IN BOTH THE FEDERAL GOVERNMENT AND PRIVATE INDUSTRY, TO REINTRODUCE COAL AS THE FUEL FOR RAILROAD LOCOMOTIVES.

PRELIMINARY ESTIMATES INDICATE THAT RECONVERSION OF ALL THE NATION'S LOCOMOTIVES TO COAL WOULD LOWER RAIL FUEL COSTS BY AS MUCH AS 50 PERCENT AND INCREASE COAL SALES FOR THE DEPRESSED COAL INDUSTRY BY AT LEAST 20 MILLION TONS. EACH TON OF COAL UTILIZED LESSENS AMERICAN DEPENDENCE ON OPEC OIL AND STRENGTHENS OUR BALANCE OF PAYMENTS.

THIS MEANS MORE COMPETITIVE TRANSPORTATION RATES, LOWER COSTS OF GOODS TO CONSUMERS, AND THOUSANDS OF JOBS FOR U.S. COAL MINERS AND RAILROAD WORKERS.

RAILROADS ARE THE LIFEBLOOD OF OUR ECONOMY, TRANSPORTING VITAL GOODS TO EVERY CORNER OF THE UNITED STATES. THE RAIL SYSTEM IS A PART OF THE FOUNDATION OF OUR COUNTRY'S NATIONAL DEFENSE. IN TIMES OF NATIONAL EMERGENCY, THE UNITED STATES IS EVEN MORE DEPENDENT ON OUR RAILROAD TRANSPORTATION SYSTEM.

IN 1981, DEISEL FUEL BURNED BY RAILROADS REPRESENTED 12.4 PERCENT OF TOTAL U.S. CONSUMPTION OF OPEC OIL. BECAUSE OF THE POSSIBILITY OF INTERRUPTION OF FOREIGN OIL SUPPLIES DURING NATIONAL EMERGENCIES, THE DEPENDENCE OF OUR NATIONAL RAILROAD SYSTEM ON IMPORTS OF OPEC OIL MUST BE REMOVED. THE BURNING OF COAL BY LOCOMOTIVES WOULD REDUCE OIL IMPORTS AND RELEASE AVAILABLE SUPPLIES OF DIESEL FUEL FOR OTHER NATIONAL NEEDS. THIS IS VITALLY IMPORTANT TO OUR NATION'S ECONOMY, ENERGY INDEPENDENCE, AND NATIONAL SECURITY.

THIS MORNING, WE HAVE A DISTINGUISHED PANEL OF WITNESSES WHO ARE WELL-QUALIFIED TO TESTIFY ON RESTORING COAL AS THE PRIMARY FUEL FOR RAILROAD LOCOMOTIVES. I WELCOME ALL THE WITNESSES AND LOOK FORWARD TO THEIR TESTIMONY.

Senator WARNER. This morning we have a distinguished panel of witnesses to testify on the possibility of restoring coal as one of the principal fuels in our system. I welcome all the witnesses. Mr. William Withuhn is an expert on railway economics and vehicle design. Although he is testifying this morning as a private consultant, the record will also show that he is the Deputy Chairman of the Smithsonian Institution's Department of Science and Technology. We welcome you this morning.

STATEMENT OF WILLIAM L. WITHUHN, CONSULTANT ON RAILROAD ECONOMICS AND OPERATIONS

Mr. WITHUHN. Thank you, Senator Warner, and other members of the subcommittee and staff. I appreciate your invitation to appear at these hearings.

Let me stress at the outset that, since I am a named coinventor in patent proceedings and hold a small interest in one of the proposed design options for a modern, coal-burning locomotive, I am here today strictly as a private citizen, on my own time. My employer takes no position in these hearings.

Before coming to Washington, I was a senior management and operating officer in a medium-sized group of freight railroads, with common carrier operations in three States. These freight operations are quite successful financially, partly due to the aggressive policy of cost control, and it is in that context that I would like to address the subcommittee.

My knowledge is first hand, not simply theoretical. In the topics you have asked me to comment on—the history of railroad use of coal as a fuel and the feasibility and wisdom of its reintroduction—the practical issue of cost control for the railroads is paramount. I mean cost control in its complete sense, where fuel cost is only one consideration. It is certainly not a question of nostalgia and only partly a question of secondary economic effects.

Until about 1950, coal was the basic railroad fuel. In 1929, for example, 57,000 steam locomotives were running in this country, and over 90 percent were fired on coal. The other steam locomotives, used by railroads in the Far West where coal was not then as abundant as in the East, were fired on bunker oil. Over 100 million tons of coal were consumed from American mines for locomotive fuel in 1929. Railroads were one of the coal country's biggest customers.

That coal produced the energy to haul nearly one-half trillion ton-miles of U.S. freight, in an era when the railroads hauled practically everything over medium and long distances. To hear some tell it now, one would think U.S. railroads couldn't carry much of anything over any distance before the age of diesel, due to all the various problems that were experienced in those days by traditional-type steam locomotives. Those one-half trillion ton-miles were produced on a 7-days-a-week, 12-months-a-year schedule, in all sorts of weather, with one-time records that have not been improved upon significantly.

By 1944, a war year, and with newer, more efficient steam locomotives in use, there were fewer locomotives, hauling more tonnage. Some 40,000 steam locomotives and 3,000 diesels handled nearly three-fourths of 1 trillion ton-miles. Again, over 100 million tons of coal was consumed as fuel, but this time to haul 50 percent more tonnage.

It is an impressive record. But there were serious operating problems with the traditional type steam locomotive, problems the diesel locomotive solved. Steamers presented the crews with working conditions that today no one would tolerate, serious smoke pollution was endemic, traction at the rails was often poor, engine and boiler maintenance was very high with the conventional type of locomotive design, and track maintenance was high because of the inherently imbalanced wheels and drive system used in American design.

Diesels, on the other hand, let the crews work in a clean environment, smoke was virtually eliminated, traction at the rails was much smoother and thus power could be delivered more effectively to the rail, locomotive maintenance was cut in half, and track maintenance was cut due to the balanced drive system that was inherent in diesel design.

As to fuel costs, diesels cut the fuel bill by about one-third, as compared to newer steam locomotives in equivalent service. But diesel fuel between 1950 and 1970 averaged 10 cents per gallon.

Diesels brought unexpected changes, whose effects are still with us. Diesel locomotives were standardized, which not only reduced drastically the spare parts inventory, it allowed locomotives to be bank financed on very attractive terms; because diesels were so standard across the country, they could be self-securing as collateral for their own purchase. Steamers, on the other hand, because they were largely custom built in relatively small batches or to unique specifications for each railroad, were often not as attractive as collateral in financing arrangements because custom designs could be readily used only on the railroad for which they were built. This problem—attractive financing for accepted, widely used designs and difficult financing for designs not widely used—is still an important factor. The financing of an untested prototype is, of course, something else entirely. The point is that railroads must consider not only price in capital purchasing but financing costs as well, even after a prototype of a new design were fully tested and proven.

Diesels changed American railroad operating practices in fundamental ways, ways that were not fully appreciated until the steam-to-diesel changeover was well along. Standard diesels, with electric controls, brought a key change: multiple-unit operation. Steam locomotives required a two-person crew in every engine, no matter how many engines might be needed to pull the train. With the diesel, any number of locomotives could be easily ganged together, all under the control of one engineer. That meant that any horsepower required could be put together quickly at the head of the train, simply by assigning two, three, four, or more locomotive units; any horsepower required—from 3,000 to 20,000—could be assembled at the locomotive dispatching point from standard, self-contained units. Thus, all the former custom building of steam locomotives, in different sizes and horsepower ratings for different jobs, was rendered academic. And thus crew costs were radically lowered; instead of needing a two-person crew in each and every locomotive assigned to a train, now just one two-person crew was needed to fully control any size train. And because any required horsepower could be assembled for that crew, trains could get much longer, reducing the number of trains for the same tonnage, reducing crew costs further still.

Hence, standardized locomotives, capable of—today—single-person operation in multiple units, is key to understanding modern railroad economics and operations. Every aspect of railroad costs is affected by this: maintenance and maintenance scheduling, inventory costs, crew costs, operating efficiencies in the matching of trains to horsepower assigned, operating efficiencies in fuel conservation, convenience of handling at servicing stops, and so on. Fuel costs were only a part of the economic rationale for giving up the old style, coal-burning steam locomotive.

In the late 1940's and early 1950's, there were attempts to make of the coal-burning locomotive a more efficient and convenient device. A number of steam turbines were tried, with failure the result, either because the turbines were too big, or too complicated, or too expensive to maintain, or all three.

Railroads, with their very severe operating environment, do not take kindly to fragile or complicated machines. Rugged simplicity is vital to success for any design that hopes to make an inroad.

Today, the economic situation has changed again. Railroad fuel costs have multiplied eightfold since 1972. Whereas in the mid-1970's locomotive maintenance and fuel costs were about tied for the two most important items of locomotive running costs—with crew costs third—today fuel costs are nearly double locomotive maintenance—and crew costs are still third. Railraods today spend $3 to $4 billion per year on diesel fuel, depending on traffic levels.

The potential of coal is best illustrated if we put the comparison on a per-Btu basis, so we can compare apples and apples. At present, the cheapest diesel fuel on bulk contract costs about $6 per million Btu's. The most expensive, low-sulfur steam coal costs $1 to $2 per million Btu's, delivered to the customer. Most low-sulfur coal from the West costs less than 50 cents per million Btu's, depending on its location. If we then add in all the other fuel-related costs of handling, ash disposal, special coaling equipment, thermal efficiency, and other changes from today's diesel locomotive, the conclusion is inescapable: U.S. railroads could cut their fuel bill by more than half, and cut their overall locomotive costs by at least half.

This conclusion has been found in several studies to this point, including ones by West Virginia University and, most notably, by Jet Propulsion Laboratory of Pasadena, in a 2-year effort funded by DOE. Even a coal-burning option that was relatively simple to build, but which would meet today's environmental standards and modern railroad operating standards, and that could be ready for commercial production within 5 years, would cut locomotive operating costs each year, over the full life of the locomotive, by half. Such a locomotive would pay for itself—including all capital, interest, maintenance, crew, and other costs— within 3 to 4 years, even if it cost much more to purchase than today's diesels.

The question for railroads today is practical feasibility: Could such a locomotive be built, which eventually could be standardized, that would haul the trains, day in and day out? Could it be built and not entail excessive maintenance costs, or crew costs, or fuel handling costs? And would it meet environmental standards?

There are a host of technical issues, from antislip control and adhesion maximization, to dynamic braking and lateral-to-vertical wheel loadings under dynamic conditions. But after 10 years of study on the matter, and with my own experience, I believe the technical issues can all be solved. And the design solution can preserve and extend the operating economies which diesels brought to American railroading. It simply takes the courage to begin the effort.

The national incentives are clear. Railroads today haul over one-third of all U.S. intercity freight ton-mileage. Railroads haul more intercity ton-mileage than trucks. They haul more ton mileage than inland waterways do, or pipelines. Railroads are a vital part of our economy, and their importance is growing. By converting to coal fuel for railroads, we could put one-third of our Nation's freight commerce on a domestically produced fuel. We could insulate one-third of our Nation's freight transportation from foreign upheavals. The liquid fuel that was saved could be available to the other modes of transportation that need it: trucks, autos, and aircraft, hence exerting a powerful downward influence on oil prices.

The demand from the coalfields to put U.S. rails on coal fuel would be about 50 million tons per year. New coal burning designs would be far more efficient, and hence would use less coal than in the prediesel era. But that also means that railroad demand for coal, of itself, would not constitute a serious upward pressure on coal prices. When West Virginia University looked at that problem—upward pressure on coal prices—it was concluded that railroad demand would only go part way toward taking up the slack of idle mine capacity and excessive unemployment in the coalfields.

At present, however, the oil glut is keeping oil prices under control. The railroads have won their battle against slurry pipelines, removing that competitive threat. And the deregulation of rail rates under the Staggers Act has led, at least for now, to fairly easy passthrough of cost increases to rail tariffs and contract rates. These three factors have pretty well removed the incentive on U.S. railroads, for now, to act decisively to protect their future cost-reducing options.

There is some good experimentation going on with a much-modified diesel design which can burn micropulverized coal suspended in oil. However, there has been a lot of work in the recent past on trying to get diesel engines to run on coal, or coal-in-oil, with failure to result. Internal-combustion engines are allegeric to solid fuel, due to incomplete exhaust of the fine ash from the cylinders. There has also been work on direct coal-fired turbines, which again has not been repeated so far, although Jet Propulsion Lab feels that such a design could be ready only after a minimum of 12 years of research and development.

Recent experience with turbines in severe operating environments has not been encouraging: the new Army M–1 tank, powered by a turbine, only goes about 150 miles between major engine servicing and has a technical manual that runs to 61,000 pages. Railroads need a higher reliability standard and far less complexity in their vehicles.

Meanwhile, coal is making a comeback in another mode of freight transportation: shipping. The $37 million coal-carrying vessel *Energy Independence,* just completed this year, is now moving coal between Norfolk and New England. And she burns the same kind of fuel she carries. She bears about as much resemblance to old, coal-fired ships as new steam locomotives would bear to traditional locomotives. Her automated-coal and ash-handling equipment, for example, means a crew size about the same as a modern oil-fired vessel. Of course, some had felt that the *Energy Independence* was not worth trying, just as some feel today that coal as a railroad fuel should not be encouraged.

The outlook for new, coal-fired locomotives is excellent, from a technical point of view. That was the conclusion of Jet Propulsion Lab, which indicated a 5-year timeframe to develop a first-generation, new design which would be as cheap to operate as any other option available in this century. A high degree of technical feasibility was also the conclusion of Burlington Northern Railroad, after a 6-month study of practicality, support and service needs, and economics.

The problem is an old one: the ability of new, innovative proposals to gain the financing needed to try them out. Railroads are great risks avoiders. So long as everyone else uses the same type of locomotive, why worry about big cost-reduction possibilities 5 or 10 years away? There is frankly little incentive, short of a new Mideast war. And the established locomotive builders have no incentive to make radical changes in their product line; small, incremental changes are change enough.

Whether there is a role here for limited Government involvement, in the historic model of helping sponsor research and development in the broad public interest, I must leave to the Congress. Thank you.

Senator WARNER. Thank you. Before we go any further, I should assure those observing this hearing that we are not returning to the old whistle-blowing steam locomotives of the past, spewing sparks and cinders all over the countryside. Indeed the advantages that you describe in the transition from the old steamer to the existing diesel fuel will not allow as to step back. We are going to keep all of those advantages, is that correct?

Mr. WITHUHN. Indeed; that is correct.

Senator WARNER. One of the principal impetuses that goes with this technology is the present need to find cheaper fuel oil for its railroads. It appears that the difference in price of oil to coal has been on the increase recently.

Mr. WITHUHN. On the increase over the last 10 years.

Senator WARNER. Another impetus for this new technology is a need for America to be less dependent on overseas oil, and to provide for employment in the rail and coal industry. So we've got three very powerful incentives to move in this direction.

Could you expand on the various options that are likely to come forth here? Did you say it would be clean or cleaner than the existing diesel?

Mr. WITHUHN. It turns out the diesel locomotives are relatively benign in their pollution effects. In fact, they are not even regulated as to pollution by the EPA. In fact, with the design that I was associated with we used even further stringent controls.

So a good answer in the short term will be to use low-sulfur coal in a gas-producing mode, which then allows a limited cleanup to take place to produce an exhaust gas that by almost every measure is below pollution levels produced by the diesel. In fact, it is much more favorable and less of a polluter than nitrogen oxide, which is the prime problem by smog.

In the long run, the favored option would probably go to fluidize form of combustion whereby sulfur cleanup can take place.

Even in the short run, there is abundant low-sulfur coal available in the West.

Senator **Warner**. And the East, in Virginia.

Mr. **Withuhn**. And the East. Indeed. I look at the economic use of the low-sulfur coal available in the eastern conference and discovered there was a 2-to-1-ratio advantage in cost.

Senator **Warner**. You pointed out the reluctance in industry to convert to coal-fired diesels. There are two principal manufacturers of diesel locomotives in the United States today, and a number of rail systems that are functioning reasonably well economically. There is also present an understandable hesitancy on the part of the rail systems and the two principal manufacturers to begin to put substantial amounts of their dollars into a research and development program.

The Norfolk Southern system located in Virginia has made just such an investment. They consider this option of going to coal substantially important and are willing to put their own dollars up. But the question really is whether those dollars will be sufficient, and whether or not the Federal Government should come in on some type of matching basis or incentive basis and devise a program. Should the Government build two or three different types of coal-fire locomotives, and then let industry determine whether or not these options are economically and technically viable. If so, then let the private sector take over and build in substantial numbers.

Back to the question. What sort of a Federal program do you think would be appropriate?

Mr. **Withuhn**. Well, the capital needs required to build in a short-term option will only build one rather than several, which I think would be——

Senator **Warner**. Just build one?

Mr. **Withuhn**. Build several would be wise. The problems with the railroads, as I see it, is they have to preserve their options. If they put a great deal of money into, say, one option, that would in effect kind of close them out possibly from another favorable option a bit later.

So I think they are reluctant to put in more than a few million here or there to try and keep this thing active, and certainly to investigate it.

Senator **Warner**. Let's make the record clear. Our records indicate $50 to $70 million for a prototype.

Mr. **Withuhn**. That would be the R&D cost, the engineering time, all various testing time to do a feasible prototype.

Senator **Warner**. That prototype would be full size, operative on today's rail systems?

Mr. **Withuhn**. Indeed.

Senator **Warner**. And approve or disapprove its technical and economic viability.

Mr. **Withuhn**. The only other thing that would have to go along with it is the support system. For example, you could handle the coal in small containers. There isn't any going back to the old, dirty, coal-burning days.

Senator **Warner**. Maybe we could put the whistle back on though.

Mr. **Withuhn**. That has been insisted by a number of people.

Senator **Warner**. That is very helpful. Will you be able to stay for a while this morning?

Mr. **Withuhn**. Certainly.

Senator **Warner**. I think it would be helpful if you heard the other witnesses, and perhaps you would have further comment at the conclusion of the other witnesses.

We will turn now to Mr. Sid Liddle who testifies this morning on behalf of the Jet Propulsion Laboratory [JPL] of the California Institute of Technology. When I was Secretary of the Navy I worked a great deal with your distinguished institution, and I was very pleased to learn of this special project that you and others at JPL have been working on. So much of your work is in national defense.

Mr. Liddle was the task manager for a 1981 Jet Propulsion Lab report entitled "Future Fuels and Engines for Railroad Locomotives." In reviewing this I noted that several companies providing technical information for the Jet Propulsion Laboratory study have already testified before the subcommittee, or will do so on January 9. They include General Motors, Southern Railway, Chessie System, and General Electric. We welcome you, Mr. Liddle.

STATEMENT OF SIDNEY G. LIDDLE, JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY

Mr. **Liddle**. Mr. Chairman, thank you very much for this opportunity to appear before you to discuss the coal-fired locomotives.

I have a prepared statement which I would like to submit for the record, and I would summarize the content of that statement.

Senator **Warner**. We will accept that statement.

Mr. **Liddle**. The Jet Propulsion Laboratory in 1978 began a project sponsored by the Department of Energy to assess ways of reducing the dependency of the railroads on petroleum fuels, and to determine technical areas for new research. I was the manager of this effort. Several different approaches were taken. One was to examine the modifications to be made to diesel and electric locomotives to improve fuel economy. Several modifications being evaluated are listed under table 1 in my prepared statement and this slide shown here.

Basically the modifications to the locomotives could improve fuel economy by up to 20 percent. However, gains in excess of 20 percent are not likely since the diesel engine is already very efficient and at the top of its ability to advance further.

Advanced diesel engines are another subject that was examined. The present-day diesel engine was used as a base. It has a thermo efficiency of 40 percent and produces 3,000 horsepower. This is a typical operative size.

This engine is turbocompounded which covers part of the exhaust. Efficiency is 44 percent, and the operative power rises to 3,485 horsepower.

Changing the diesel into an adiabatic diesel increases the efficiency to 49 percent. Further changes can raise the efficiency 62 percent using the features under 2.5, which is the bottom item on that list.

An adiabatic diesel engine can be the most efficient heat engine known. The problem with this approach is the large ceramic components necessary in the engine of this type for locomotive service, since the failure rates of ceramic components are in proportion to their volume. Production of reliable ceramic components necessary for locomotive engines is years away, probably around the year 2000. It's going to be a major R&D just to do that.

The diesel engine is not the only engine which is being used in locomotives. Steam engines and gas turbines have been used in the past. Table 4 lists some of the engines investigated in this survey. I have already discussed the diesel engine. We have also looked at reciprocating steam engines, and steam turbines, and several versions of gas turbines and Stirling engines. In this table, which is table 3 of the prepared statement, the thermal efficiency has a number of different engines shown. They range from 20 percent for first generation of steam engine to around 64 percent for a long-term, mature, adiabatic diesel. The long term mature engine is an adiabatic diesel engine with all the fuel saving modifications we thought were possible. This sort of represents the limit of what could be done. This table indicates the engines based on the adiabatic diesel are more efficient, and the steam engines are the least efficient, and the gas turbines are comparable with the present day diesel engine.

Fuels other than diesel used played a major role in our study, 44 fuel emulsions were investigated for use in the different engines.

This slide shows some of the different kinds of fuels examined for use in the diesel engine. Most of these fuels can also be used in gas turbines and Stirling engines, and some can be used with fuel cells.

The technical aspects of the locomotive are only part of our study. Economic aspects of the different engines were also explored. Life cycle cost analysis to measure the relative economic findings of the locomotives. This slide is showing the different costs used in our analysis. We attempted to be as consistent as possible in all cost variances with the different locomotives. The results are given in terms of dollars should be used in a comparative sense rather than absolute. We were projecting on approximately a 20 year period, and I don't think that can be done in any real absolute basis.

The results of the analysis for the alternative fuel, the ranking show in this slide, table 6, emerged and argued that the relatively small range of life cycle cost indicate that the use of alternative fuels in the present diesel electric locomotive will provide fuel availability, but at no appreciable savings to the railroad.

A different picture emerged when we tied our results to different engines. A portion of the results are shown in this slide, table 7, of the prepared statement. All of the lowest life-cycle costs, regardless of the engine, are fueled with coal. By comparison, the high efficiency long-term-mature diesel has a life-cycle cost considerable higher than the steam engine, with the reciprocating drive that had only 20 percent efficiency.

The reason for this apparent anomaly is explained on this slide, table 8, with the life cycle costs broken down into various categories. The top one refers to the present day diesel-electric locomotive using diesel No. 2. The largest cost item for this locomotive is fuel, which amounts to 76 percent of the total. The last item is closed cycle gas turbine. On this locomotive the capital cost, the maintenance cost, and the operating cost are all higher than for the diesel electric. The coal cost for this locomotive is, however, a fraction of the cost of the diesel-electric fuel. It is the fuel cost that makes the coal-fired locomotive economically attractive.

The locomotive manufacturers have been modifying present engines to provide better fuel economy. Alternative use for this engine has been the subject of the program at the Southwest Research Institute. This program has been sponsored by the Department of Energy, the Association of American Railroads, General Motors, and General Electric. Coal combustion has been the subject of Department of Energy research for many years, but not for locomotive application.

The results of our study indicates there are clear economic gains that can be made by introducing coal back into the locomotive. There are, however, a number of technical problems associated with the reintroduction, not the least of the problem, the determination of which coal-combustion system and which engine is best suited for this application. There is research in areas of remote control, coal-combustion equipment, logistics, and engine. Thank you, Mr. Chairman. I'd be happy to answer any questions.

[The prepared statement of Mr. Liddle follows:]

Prepared Statement of

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to the

Subcommittee on Energy and Mineral Resources
Senate Committee on Energy and National Resources

20 December 1983

INTRODUCTION

Presently, the American railroads ship over 35% of the freight in the United States. This service is second only to pipelines and barges in energy efficiency and serves a wider range of customers. Because about 99% of their fleet consists of Diesel-electric locomotives, the railroads are dependent on the supply of Diesel No. 2 fuel. This fuel oil has changed from a relatively cheap and readily available commodity to one having an increasingly limited supply and higher cost. There has been, therefore, a growing interest in improving the fuel economy of locomotives and also in finding alternative fuels for use in these same engines.

A study was sponsored by the Department of Energy to assess ways of reducing the dependency of the railroads on petroleum fuels and to determine the technical areas where new research was needed . This work was performed by the Jet Propulsion Laboratory under Interagency Agreements EM-78-1-01-5151 and DE-A101-78C55151 through NASA Task RD 152, Amendment A189. The results of the study was published as JPL Report 81-101, dated November 1, 1981.

Comparisons were made between the current Diesel-electric system, improved Diesel-based systems, and new systems using other engines and power sources. These comparisons identified the most promising improvements to the Diesel-based systems for short term applications and the most promising successors to the Diesel in the longer term.

In the short term, it is desirable for locomotives to be modified for energy conservation and alternative fuels. In the long term, an assessment must be made as to whether the Diesel-electric is to remain the preferred system. Due to the high capital costs, electrification is attractive only for high traffic density lines. These lines form only a small percentage of the railroad routes in the United States. Therefore, there will continue to be a need for locomotives that carry their own energy supply.

DIESEL-ELECTRIC LOCOMOTIVE MODIFICATIONS

The present day locomotive Diesel engines are highly developed but there is some room for improvement in the combustion chamber, the valves, and the fuel injection system. These changes are more evolutionary than revolutionary in nature. Among the possible engine modifications examined were increased maximum cylinder pressures, increased turbocharger boost pressures, and reduced piston speeds. A loss of power due to reduced engine speed can be countered by an increase resulting from the higher cylinder pressures. There is no modification to existing engines that would have a significant effect on fuel consumption except the addition of exhaust heat recovery systems.

Approximately one-third of the energy in the fuel leaves the engine in the exhaust gas. One way of increasing the overall thermal efficiency of the engine system is to recover some fraction of this energy and turn it into useful work. Bottoming cycles are one means of recovering this energy and there are two applicable types:

(1) Power generating cycles.

(2) Fuel reforming cycles.

The power generating cycles convert exhaust energy into useful work through such options as turbocharging, turbocompounding, Rankine engine compounding, and Stirling engine compounding. Turbocharging is already in use on many locomotive engines. Retrofitting of turbochargers to existing non-turbocharged engines is possible and, in many cases, desirable.

In fuel reforming cycles, the exhaust energy is used to convert a liquid fuel into a gas mixture that has a higher heating value than that of the original liquid fuel. Direct decomposition and steam reforming are the most attractive of these cycles. Each of these two cycles are suitable only for certain fuels. Direct decomposition is practical only for methanol. Methanol and ethanol can be steam reformed using the exhaust energy from conventional Diesel engines. Steam reforming of hydrocarbon fuels requires higher exhaust temperatures and is only marginally suitable for adiabatic Diesel engines. A variation of this type of cycle is the partial oxidation of the fuel with heat recovery from both the partial oxidation process and the engine exhaust.

In addition to the modifications of the engine, modifications to the rest of the powertrain must be considered. The auxiliary equipment, the transmission, and the dynamic braking system, all use engine power and affect the fuel consumption of the locomotive as a result.

The auxiliary power used for the equipment blowers, air compressors, radiator fans, and auxiliary generator on a typical 3000-hp locomotive ranges from about 25% of gross engine output in notch 1 to 6% in notch 8. The major items are the equipment blowers and the radiator fans that absorb about 215 hp in notch 8.

Table 1. Diesel Locomotive Modifications

1. Rankine compound bottoming cycle
2. Direct decomposition of methanol
3. Stirling compounded bottoming cycle
4. Increased turbocharger boost pressure
5. Increased maximum cylinder pressure
6. Turbocharger retrofit
7. Accessory power reduction
8. Dynamic braking engine power reduction
9. Reduced piston speed
10. Partial oxidation fuel reforming
11. Steam fuel reforming
12. Electric transmission modifications
13. Leaning out the air-fuel ratio

Present versions of dynamic braking require using the engine to provide power for fans and blowers during braking. The power generated in the dc motors is dissipated in resistor grids. Ideally, it should be possible to supply all of the power needed by the locomotive from the dynamic braking power. Unfortunately, this power is not always in a usable form. The voltage of the power from the motors varies with motor speed and does not match the needs of the blower motors. If the power could be conditioned using modern solid-state devices so that it could be used, then the engine could be operated at low idle during dynamic braking.

The various engine and locomotive modifications are listed in Table 1. This listing has many qualifiers attached. For example, the direct decomposition of methanol is a viable option only if methanol is a viable fuel. The Stirling compounded bottoming cycle can be used only with an adiabatic Diesel engine. The short term "mature" engine referred to later in this testimony is one combining these modifications and the maximum fuel economy improvement expected as a result is about 20%.

ADVANCED DIESEL ENGINES

The Diesel engine has been under development for nearly a century and has become an efficient prime mover. This engine, in turn, can be combined with other thermodynamic cycle engines to produce even more efficient systems. These combinations were initially discussed in connection with the bottoming cycles for use with conventional Diesel engines. Advanced Diesel engines combine unconventional Diesels with various bottoming cycles to produce multiple cycle engines that can achieve efficiencies well in excess of today's engines.

A series of Diesel engine changes are shown in Table 2. Engine 2.1 is a four-stroke locomotive Diesel engine rated at 3000 hp. The turbocompounded

Table 2.

	Engine	Rated Power in Horsepower	Thermal Efficiency, %	Brake Specific Fuel Consumption
2.1	Base engine	3000	40	0.34
2.2	Base engine with turbocharging and turbocompounding	3485	44	0.31
2.3	Adiabatic Diesel version with turbocharging and turbocompounding	3835	49	0.28
2.4	Adiabatic Diesel with turbocharging, turbocompounding, and gas bearings	4290	55	0.25
2.5	Adiabatic Diesel with turbocharging, turbocompounding, gas bearings, and Rankine bottoming cycle	4890	62	0.22

version of this engine, shown as Engine 2.2, has a rated output power of 3486 hp, 16% greater than the base engine rating of 3000 hp. More important, the BSFC (brake specific fuel consumption) of the turbocompounded engine is nearly 9% less.

Since most of the methods proposed to improve the thermal efficiency of the engine system depend on the use of exhaust gas energy, it is logical to try to divert the cooling system heat into the exhaust system. The adiabatic Diesel engine is shown as Engine 2.3. Instead of a cooling jacket, the cylinder is insulated to prevent heat from flowing away from the combustion chamber. Similarly, the cylinder head, valves, and piston crown are insulated. In this configuration, the amount of heat lost to cooling is reduced from 33% to only 17% of the total input energy. The exhaust gases contain about 42% of the total heat and the exhaust gas temperature has increased by 400°F to about 1300°F. The high energy content of the exhaust gas suggests that more than one heat recovery system could be used. The adiabatic Diesel shown as

Engine 2.3 has two heat recovery systems, turbocharging and turbocompounding. The last system on this table, Engine 2.5, uses three; the Rankine bottoming cycle, turbocompounding, and turbocharging. The additional heat recovery systems have a marked effect on BSFC and on thermal efficiency.

The walls of an adiabatic engine are very hot. On test engines, they are red hot. As a result, the materials and lubricants used in this engine must be able to withstand the high temperatures and the stresses imposed by Diesel engine operation. Ceramics are, therefore, an integral part of the adiabatic engine design because no other known class of materials will stand up to the high temperatures.

The lack of high temperature lubricants is a major problem in developing the adiabatic Diesel engine. There are solutions available, however. One solution is to eliminate lubricants entirely. The minimum friction engine uses this approach. Gas bearings are used in the piston-cylinder liner interface and ceramic roller bearings for the wrist pins, crank pins, and main crankshaft bearings. Solid lubricants would be used for gears, valve guides, rocker arms, and push rod assemblies. One version of the minimum friction engine is shown as Engine 2.4. This version uses only the gas bearing at the piston-cylinder liner interface and uses a conventional oil system for the remaining bearings.

The addition of a Rankine bottoming cycle to the fourth configuration to form the fifth one results in an output power rating of 4890 hp and a BSFC of 0.22 lb/hp-hr corresponding to a thermal efficiency of 62%. The exhaust gas from this engine system contains only 12% of the input heat. Approximately one-third of the heat wasted by the base engine has been recovered in this engine to produce useful energy.

The gains in efficiency are as impressive as the problems of developing the engine. The ceramic parts needed are larger than any yet made from these materials. A better understanding of the failure modes of ceramics is needed. The reliability of ceramic parts in this kind of application must be established. The savings in fuel, and in fuel costs, possible with the adiabatic engine provide a strong motivating force to solve these problems.

The various advanced Diesel engines and a number of other engines are ranked in Table 3 by their thermal efficiency. The adiabatic Diesel engines show the greatest potential for increased thermal efficiency. Not shown in this table are the partial adiabatic engines that use a combination of ceramic and cooled metallic components. They may be thought of as intermediate steps in the development of an adiabatic Diesel engine but they are practical engines in their own right. It may not be possible to build a fully adiabatic engine of the size necessary for a locomotive but a partial adiabatic could still provide a substantial gain in thermal efficiency.

The "mature" or "ideal" Diesel engines are also included in Table 3. These engines are not really practical engines but were conceived to de-

Table 3. Ranking of Engines by Thermal Efficiency

Engine	Notch 8 Thermal Efficiency, %
1. Long term "mature" adiabatic Diesel engine	64
2. Adiabatic turbocompound Diesel engine with minimum friction and Rankine bottoming cycle	59
3. Adiabatic turbocompound Diesel with Rankine bottoming cycle	54
4. Adiabatic turbocompound Diesel with minimum friction	52
5. Adiabatic Diesel with Stirling engine bottoming cycle	51
6. Short term "mature" conventional Diesel engine	50
7. Phosphoric acid fuel cell using methanol	49 (46)[b]
8. Conventional Diesel fueled by directly decomposed methanol	47
9. Advanced Stirling engine using liquid fuels	46
10. Conventional Diesel with Rankine compound bottoming cycle	45
11. Open cycle, internal combustion regenerative gas turbine	42
12. Closed cycle, external combustion regenerative gas turbine[a]	40
13. Present Diesel engine	40
14. Open cycle, external combustion regenerative gas turbine[a]	39
15. Advanced Stirling engine using a fluidized bed combustor	39
16. Advanced stratified charge rotary combustion engine	35
17. Second generation new steam engine	28
18. First generation new steam engine	20(17)[c]

Notes: [a] Efficiency based on shaft power to alternator using ceramic heat exchanger in fluidized bed, turbine inlet temperature is 2250 °F.

[b] Efficiency based on dc output rather than shaft power. Equivalent shaft efficiency will be 49%.

[c] Efficiency based on cylinder output to wheels, equivalent shaft efficiency will be 20%.

termine the thermal efficiency limits of Diesel engines. One engine, the short term "mature" engine is based on a water-cooled engine of essentially conventional design using the various modifications investigated in this study. The other engine, the long term "mature" engine is based on a fully adiabatic engine with all of the modifications, bottoming cycles, and other locomotive changes.

The Diesel engine is capable of much higher thermal efficiencies than present engines if multiple thermal cycle systems are used. A well-developed adiabatic Diesel with two or three stages of exhaust heat recovery will probably be the most efficient heat engine possible. However, the complexity of this engine system must be considered along with the fuel and cost savings.

Advanced Diesel engines using adiabatic engines will require considerable development. Ceramic components for engines as large as a locomotive engine are not available and will not be available for many years. It is not expected that adiabatic engines for locomotives will be available before the year 2000. An adiabatic Diesel engine burning coal represents the ultimate combination of a high efficiency engine and a low cost fuel.

ALTERNATIVE ENGINES

The Diesel engine is not the only engine that can be used for powering a locomotive. Over the last century and a half, reciprocating steam engines, steam turbines, and gas turbines have all been used. If the railroads' dependency on Diesel No. 2 fuel is to be reduced, it is necessary to examine engines other than the Diesel.

Table 4 lists the principal engine types and the specific versions examined in this study. There are numerous variations of these generic engine types. No attempt has been made to explore all of the possible engines but rather to determine the relative merits of the various generic types. For this study, the fuel cells are considered engines although, they operate on principles quite different from the other engines. The sodium heat engine, also known as the alkaline metal thermal energy converter, operates on principles different from either the fuel cells or the other engines.

Steam engines or Rankine cycle engines were used for nearly a century and a half by the railroads until they were replaced by the Diesel-electric locomotives. A new steam engine would bear little resemblance to the old engines except that the working fluid in the engine will be steam. The biggest change will be in the coal combustion system. The old locomotives at full power could lose half of the coal, unburned, up the stack. The efficiency of new combustion systems would be 90 to 95% in notch 8.

The basic system used by Rankine cycle steam engines is the same, regardless of whether it is a turbine or a piston engine. With new advances in cylinder lubrication and ring materials, the efficiency of the piston engine is approaching that of the turbine at full load and may be better at part load. The system efficiency of these engines will be, at least 13%, and may be as high as 25%.

The gas turbine was used in the past by the railroads. These old gas turbines were simple cycle, internal combustion engines and had a number of problems, including blade erosion and high fuel consumption. Any new gas turbine should be regenerated. That is, exhaust energy should be used to heat the compressor outlet air.

Three types of regenerative gas turbines were examined for use in a locomotive; internal combustion open cycle, external combustion open cycle, and external combustion closed cycle. The internal combustion open cycle engine is dependent on liquid or gaseous fuels. The external combustion gas turbines can use a wide variety of fuels such as coal, wood, and crude oil as well as other liquid and gaseous fuels.

The Stirling engine has the potential to be more efficient than the Diesel engine. As yet, this potential has not been demonstrated. The Stirling engine is a much more complex engine, both mechanically and thermodynamically, than the Diesel or the other alternative engines examined. In the Stirling, the working fluid is moved between cylinders or between the top and bottom of the same cylinder. Because it is an external combustion engine, the Stirling can also use a wide range of fuels.

Fuel cells are also attractive for locomotive applications in the middle to late 1990s and beyond. They combine high efficiency (50% and above) with simplicity of operation. The fuel is converted into electricity without all the moving parts typical of the Diesel-electric locomotives. At present, the only fuel cell sufficiently developed to be seriously considered is the phosphoric acid cell. The only fuel which is attractive for this application is methanol decomposed into a hydrogen-rich gas.

ALTERNATIVE FUELS

A alternative approach to reducing the dependency of the railroads on petroleum-based Diesel No. 2 fuel is the use of non-petroleum fuels and petroleum fuels other than Diesel No. 2. These alternative fuels may be alcohols, coal and liquid fuels derived from coal, oil shale derived hydrocarbon fuels, vegetable oils, and inorganic fuels such as hydrogen. In addition, there are the blends, slurries, and emulsions that can be made from these fuels and from petroleum-based fuels. The number of candidate fuels is over 30 and there are a large number of blends, slurries, and emulsions. The total number of possible fuels is in excess of 100.

Alternative fuels have been used by the railroads in the past. Wood and coal were used by steam locomotives for well over 100 years. In fact, it was an earlier energy crisis that forced the railroads to switch from wood to coal in the late 1800's. Several railroads, including Southern Pacific and Union Pacific, have used residual oils in Diesel engines at various times. Coal and residual oils have been used in gas turbine locomotives.

Table 4. Types of Engines

Diesel engines

- Conventional with exhaust heat recovery
- Modified conventional
- Partial adiabatic
- Full adiabatic with exhaust heat recovery

Steam engines

- Reciprocating drive
- Steam turbine-electric

Gas turbines

- Open cycle, internal combustion
- Open cycle, external combustion
- Closed cycle, external combustion
- Reacting gas, external combustion

Stirling engines

- Liquid fueled
- Solid fueled

Otto cycle

- Stratified charge rotary
- Naval Academy Heat Balance engine

Other

- Fuel-cell
- Sodium heat engine

A list of candidate fuels for use as straight fuels is presented in Table 5. These fuels are divided into groups based on their source except for the alcohols, hydrogen and ammonia. Emulsions, solutions, slurries, and blends of fuels may be used in addition to the straight fuels.

The use of an alternative fuel in an engine affects more than just the engine itself. The storage of the fuel on the locomotive and at a refueling terminal must be considered. Safety hazards, toxicity and material compatibility are as important as viscosity and heating value. As a replacement fuel in Diesel engines, the oil shale distillate is the most attractive of the non-petroleum fuels. No modifications to the engine or locomotive are required. It is well suited to the medium speed Diesel engine and the prospects for an adequate supply at a competitive price in the year 1995 appear good.

For non-Diesel engines, coal is the best fuel when used in an external combustion engine system. The supply is ample and stable. Its cost is expected to remain well below that of petroleum or synthetic hydrocarbon fuels in the foreseeable future.

The biggest drawback to its use is that it is a difficult fuel to burn cleanly and efficiently. The biggest problem facing the coal-fired locomotive is the development of a combustion system that will burn the coal in an efficient and environmentally acceptable manner and that will fit into a locomotive.

There are a wide variety of ways to burn coal. These can be grouped into four main classes: direct open-chamber, direct in-bed, gasification, and liquefaction. Direct open-chamber combustion burns coal by the injection of powdered coal or by the use of a grate. Direct in-bed combustion is the complete burning of the coal in a bed of some other material. The bed may be a fixed bed or a fluidized bed and the bed material may be either inert or one that reacts with a combustion product. Coal gasification is an indirect combustion system. The reactions are in two main steps: (1) the production of the coal gas, and (2) the combustion of the gas with air. The two reactions are separated in both time and space. Liquefaction is a similar process except that the intermediate product is a liquid rather than a gas. The coal liquid is not likely to be consumed immediately and may, in fact, be further processed before it is used.

Of these four classes, only the direct in-bed and the gasification types are likely to be used on a locomotive in which raw coal is carried as the fuel. The use of coal-water suspensions instead of raw coal is possible and best suited to the gasification process. The technology of coal combustion has improved in the last 10 years to a point where it now appears feasible to build a clean, efficient coal-fired locomotive.

In the future, railroads will probably use more than one fuel in their fleet of locomotives. The use of one fuel in the past was convenient and economical, but now, economics and supply problems dictate a multi-fuel future.

LIFE-CYCLE COST ANALYSIS

Many of the new engines are technically feasible for use in line haul locomotives. Many of the fuels are also technically feasible for use in these engines. The economic feasibility of both the engines and the fuels, however, must be considered. The relative economic merits of these engines

Table 5. Candidate Fuels for Diesel Engines

Petroleum

Diesel No. 2
Gasoline
Light distillate
Naphtha
Lube stock
Broadcut fuel oil
Jet A
Kerosene
Methane
Butane
Propane
No. 4 fuel oil
No. 5 fuel oil
No. 6 fuel oil

Coal

Powdered coal
Coal derived gasoline
Coal derived distillate
Solvent refined coal

Oil Shale

Oil shale distillate
Oil shale gasoline

Inorganic

Hydrogen
Ammonia

Alcohols

Methanol
Ethanol

Vegetable Oils

Cottonseed oil
Corn oil
Peanut oil
Olive

Tar Sands

Syn-crude

and fuels have been ranked in terms of their life-cycle costs which include capital, fuel, maintenance, and operational costs.

To have consistent cost figures for all of the cost areas, it is necessary to have a single cost reference. For this study, it is the Wholesale Price Index. Values of the index for the past 20 years were used to predict values for the next 20 years. From these values and historical data, cost correlations in terms of constant dollars were established and cost predictions for specific fuels, maintenance, and other parameters were computed. These predictions were then modified depending on whether the particular cost was expected to increase at a lower rate than inflation, at the same rate, or at a higher rate. Once all of the costs were calculated, they were combined to compute the annualized life-cycle cost for each engine-fuel combination being considered. Eighteen fuels and 18 engines were used for the final evaluation.

Table 6 shows the life-cycle costs for 16 fuels used in a conventional present day Diesel engine modified as necessary to use the specific fuel. In some cases, a fuel tender must be used and its costs are included. Except for the last three fuels; hydrogen, ammonia, and ethanol, the rest of the fuels are nearly the same in cost, differing from that of Diesel No. 2 by less than 13%. Since the uncertainty of the calculation is probably near 10%, it can be concluded that the costs are basically equal. The use of an alternative liquid fuel in an engine does not reduce costs but does increase availability.

Table 6. Ranking[a] of Fuels for Conventional Diesel Engines by Annualized Life Cycle Costs

Ranking	Fuel	Annualized Life-Cycle Cost
1	Oil shale syn-crude	$1,028,000
2	Oil shale distillate	1,036,000
3	Propane	1,047,000
4	No. 6 fuel oil, low sulfur	1,090,000
5	Broadcut fuel oil	1,104,000
6	Coal derived gasoline	1,114,000
7	N- Butane	1,137,000
8	Coal derived distillate	1,139,000
9	Methanol	1,150,000
10	Oil shale gasoline	1,173,000
11	Diesel No. 2	1,175,000
12	Gasoline	1,215,000
13	Methane	1,232,000
14	Hydrogen	1,569,000
15	Ammonia	2,024,000
16	Ethanol	2,676,000

[a] All fuels used in conventional Diesels modified to accept the fuel and dual-fueled when needed.

The ranking of 12 engine-fuel combinations are shown in Table 7. In this table, there are marked differences in life-cycle cost, ranging from a low of $554,000 to a high of $1,175,000. There are some engine-fuel combinations which have higher life-cycle costs but since they are not economically attractive, they have, therefore, not been included in these lists. One example is an internal combustion gas turbine using ethanol. A first generation steam engine using Diesel fuel is another. Oil-fired steam engines were used by some railroads before the switch to Diesel engines. Today, the cost of operating such an engine would be extremely high.

The important thing about this table is the fact that all of the lowest cost options are coal-fired. Four types of engines are represented in this group and it is apparent that the type of engine and its efficiency are secondary to the fact that they are coal-fired. The most efficient and least costly of the advanced Diesel engines is 21% more expensive to operate than the least efficient and most costly of the coal-fired options. The reason for this difference is apparent once the various cost categories are examined in detail.

These figures are based on cost predictions for oil and coal made in 1979 and 1980. More recent estimates based on 1983 oil prices show much smaller savings. The new estimates show that the life-cycle costs of the long term "mature" Diesel engine to be about 10% less than that of the reciprocating steam engine, the least efficient of the coal-fired locomotives. This figure must taken with caution. Most people believe that the present oil glut is temporary and that the price of oil will be rising again in the 1990's. Since it will be 1990 before a significant number of coal-fired locomotives could be available, it is better to base the the life-cycle costs on the expected oil and coal prices then. If this is done, the results are similar to the 1979-1980 figures quoted in the JPL report.

Four of the engine-fuel combinations in Table 7 are shown in Table 8 with the life-cycle costs broken down into the four main cost areas. The present Diesel-electric locomotive using Diesel No. 2 is a high fuel cost, low capital cost unit. At the other extreme, the closed cycle gas turbine using coal is a low fuel cost unit with relatively high capital and maintenance costs. The low fuel costs more than counterbalance the other costs to a point where the closed cycle gas turbine locomotive has a life-cycle cost less than half of that of the Diesel-electric unit. Table 8 is useful in evaluating the sensitivity of the life-cycle costs to changes in fuel or other costs. For example, the doubling of coal prices relative to Diesel prices would add $157,000 to the gas turbine life-cycle cost bringing it up to $711,000.

The effect of a reduction in the locomotive usage per year can be estimated from Table 8. The operating, maintenance, and fuel costs are essentially linear functions of the locomotive usage. The coal-fired locomotive is most cost effective in those applications where locomotives use a lot of fuel but the total route usage is not enough to warrant electrification. For switch engines and most branch line service, the Diesel engine is the better choice.

The coal-fired locomotive, regardless of the type of engine used, is the only option which will provide a significant reduction in petroleum usage and reduce locomotive life-cycle cost at the same time. Alternative fuels for the Diesel locomotives provide availability but do not reduce reduce cost. Locomotive modifications reduce fuel usage and life-cycle costs by no more than 20% and then only by increasing the capital cost of the locomotive.

AREAS OF RESEARCH

Based on the results of this study, it was concluded that new research should be focused on the coal-fired locomotive. Diesel-electric locomotive modifications were already being pursued by the manufacturers spurred on by the railroads. The Department of Energy, the Association of American Railroads, General Motors, and General Electric were sponsoring research at the Southwest Research Institute into alternative fuels for the Diesel engines. The coal-fired locomotive was not even considered a likely prospect prior to the publication of this report.

Table 7. Ranking of Engines by Annualized Life-Cycle Costs

Engine	Fuel	Annualized Life-Cycle Costs
Closed cycle, external combustion regenerative gas turbine	Bituminous coal, national average price	554,000
Open cycle, external combustion regenerative gas turbine	Bituminous coal, national average price	559,000
Advanced Stirling engine using fluidized bed combustor	Bituminous coal, national average price	577,000
Steam turbine engine	Bituminous coal, national average price	608,000
Steam engine with reciprocating drive	Bituminous coal, national average price	615,000
Long-term "mature" Diesel engine	Oil shale distillate	750,000
Adiabatic turbocompound Diesel Engine with minimum friction and Rankine bottoming cycle	Oil shale distillate	793,000
Phosphoric acid fuel cell	Methanol from coal	859,000
Four-stroke turbocharged Diesel engine using directly decomposed methanol	Methanol from coal	940,000
Short-term "mature" Diesel Engine	Broadcut fuel oil	977,000
Turbocharged water-cooled Diesel with Rankine bottoming cycle	Diesel No. 2	1,101,000
Diesel-Electric	Diesel No. 2	1,175,000

Table 8. Fractions of the Annualized Life-Cycle Costs

	Capital	Operating	Maintenance	Fuel	Total
Diesel-electric using Diesel No. 2	143,000	26,000	112,000	894,000	1,175,000
Adiabatic Diesel with M.F. and R.B.C. using oil-shale distillate	137,000	26,000	112,000	518,000	793,000
Steam Turbine using national average price coal	189,000	32,000	162,000	225,000	608,000
Closed cycle, external combustion gas turbine using national average price coal	203,000	32,000	162,000	157,000	554,000

NOTES: All locomotives are assumed to be production versions

R.B.C. - Rankine Bottoming Cycle
M.F. - Minimum Friction

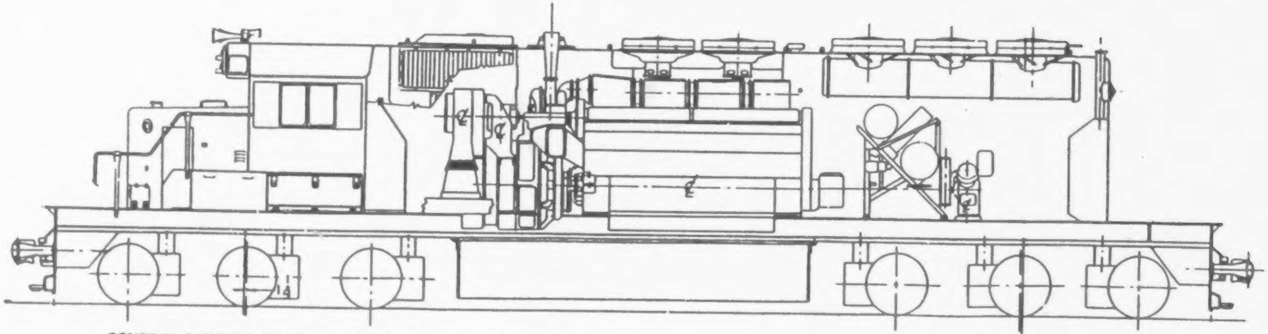
The railroads felt that a coal-fired locomotive, in spite of the attractive economics, was a high risk project and they were not sure how such a locomotive would fit into their operations. Certainly, the old steam locomotives of the 1930's and 1940's could not be used. The way locomotives are used in service had changed too much. New watering facilities were out of the question as were the restoration of firemen in the cabs. Knowing the old steam locomotives all too well, they were concerned that a new coal-fired locomotive would be as dirty and have as high a maintenance cost as the old locomotives.

The Jet Propulsion Laboratory felt that the coal-fired locomotive was an area which needed closer examination and one where it could make a contribution. The JPL approach to the design of the locomotive was to keep as much of the existing Diesel-electric locomotive as possible. Only the Diesel engine would be replaced with the coal combustion system and a suitable engine to drive the alternator. It was felt that this approach would make the locomotive as compatible as possible with existing maintenance and dispatching policies.

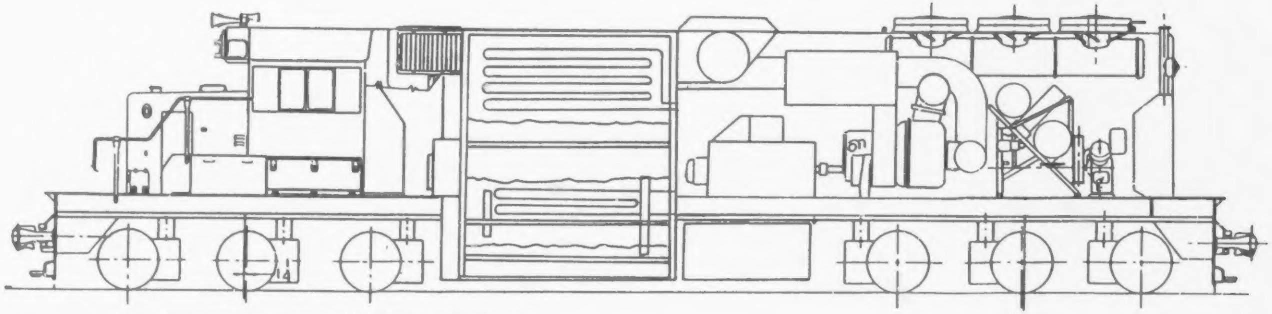
Figures 1 and 2 show three ways that a conventional Diesel-electric locomotive could be adapted to coal. The upper part of Figure 1 shows a General Motors SD40-2 locomotive. Its Diesel engine is located in the middle of the locomotive with the alternator on its left and an auxiliary equipment stand to its right. Below the Diesel engine is the fuel tank. In the lower part of the figure, the Diesel engine and the fuel tank have been removed and replaced by a Wormser type fluidized bed. A Kongsberg KG-3 turbine-generator set has been added to its right. The hood has been extended and the auxiliary equipment stand installed in the extension. This system is a closed cycle gas turbine where a working fluid is heated in the combustor. The turbine never sees the ash and sulfur in the coal.

The upper part of Figure 2 uses a coal gasifier fluidized bed which is smaller than the heater type shown in Figure 1. The coal gas from the bed is cleaned in a vortex tube cyclone and fed into the combustor of the gas turbine. The fluidized bed can be used to control the sulfur emissions and the cyclone removes the ash. In the lower part of Figure 2, a different approach is used. In this locomotive, finely powdered coal, 10 micron diameter and less, which has been de-ashed and de-sulfured, is fed directly directly into the combustor of the gas turbine. The coal which is treated before loading it on the locomotive is stored in the bin below the frame and in the bin to the left of the gas turbine. This locomotive does not require a tender to carry the coal. The other two coal-fired locomotives must have tenders.

It is apparent that there are a number of ways to burn coal cleanly and several different engines which could used with them. An advanced coal-fired locomotive project would have to study the different ways of burning coal, their application to a locomotive, the engines which would be used, the logistics of supplying fuel, and the economics of introducing these new locomotives into service. The impact of these locomotives on the environment and on the people who will operate them must also be considered.

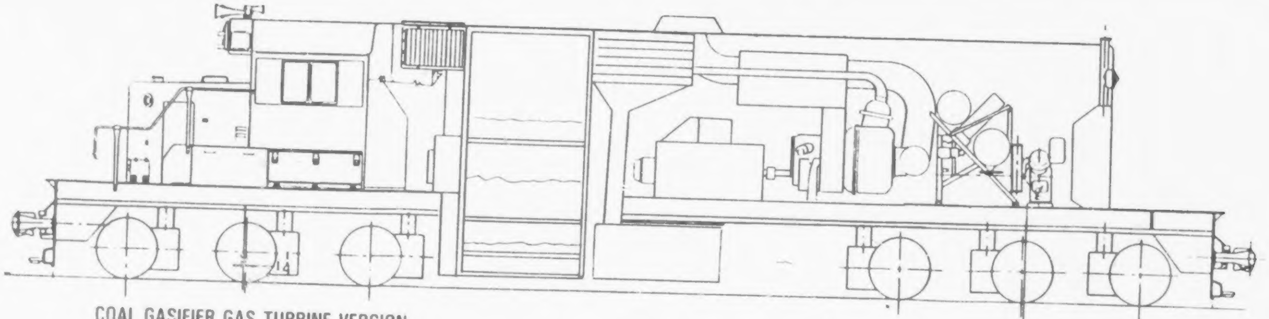


GENERAL MOTORS SD40-2 DIESEL-ELECTRIC LOCOMOTIVE

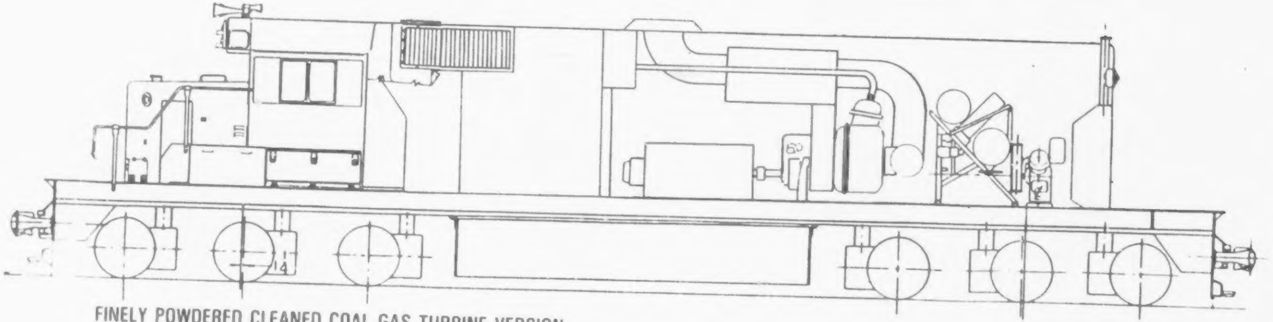


COAL-FIRED CLOSED CYCLE GAS TURBINE VERSION

FIGURE 1 ALTERNATIVE LOCOMOTIVES



COAL GASIFIER GAS TURBINE VERSION



FINELY POWDERED CLEANED COAL GAS TURBINE VERSION

FIGURE 2 TWO POSSIBLE TYPES OF GAS TURBINE LOCOMOTIVES

Such a project will require input from the railroads, the locomotive maufacturers, various suppliers, and from researchers around the country. Much of the knowledge gained from the Department of Energy coal combustion research may be applicable but the details of the combustion system must be tailored to fit the requirements and limitations of the locomotive. The same is true of engines and controls.

Coal-fired locomotives are feasible. However, which of the many possible variations are the best suited to use by the railroads is still very much an unknown.

Thank you.

Senator WARNER. Let's see if we can summarize what you have said. First, you made an exhaustive study of all of the various types of known technology today with emphasis on utilizing coal on a stock engine, is that correct?

Mr. LIDDLE. The approach we used primarily was to use as much of the present diesel locomotive as possible, giving up only the engine and possibly the alternator. This way we try to keep as much of the——

Senator WARNER. But your conclusion is clear after this study that it is a decided economic advantage to switch from diesel fuel today to a coal substitute?

Mr. LIDDLE. Yes.

Senator WARNER. And that the economic gains will justify the rail system, perhaps in combination with the Federal Government, going into research and development?

Mr. LIDDLE. Yes.

Senator WARNER. On page 12 of your report you mention that the cost facility for fuel handling, fuel storage, and waste disposal were not included in your cost calculations. In your judgment, would these costs significantly increase the costs of reintroduction of coal as fuel?

Mr. LIDDLE. It probably depends upon the particular type of coal-combustion system. But I don't see that as a major item. It would depend, to a certain extent, on the individual railroad.

Senator WARNER. Most rail systems that are colocated with major coal deposits would be the principal beneficiaries of this.

Mr. LIDDLE. They would certainly be the first beneficiaries.

Senator WARNER. When analyzing the competitiveness of coal as a fuel for railroad locomotives, did you include the costs of meeting existing environmental standards under the Clean Air Act?

Mr. LIDDLE. We looked at it. We came to the conclusion that most of the approaches that were feasible were also environmentally clean to the point that it was not significantly worse than the diesel engine.

Senator WARNER. In your testimony the statement is made that coal-fired locomotives are not expected to constitute more than 20 percent of the future locomotive fleet by the year 2000. Is there a reason for that cap?

Mr. LIDDLE. As you saw, the capital, maintenance, and operating expense of the coal-fired locomotive is higher than the diesel. If you were using it only for low use, your fuel savings is small. It is actually going to be more economical to use diesel. So at some point there is a cross over.

Senator WARNER. Those are operating standards, is that correct?

Mr. LIDDLE. Let's say you had an engine for switching service.

Senator WARNER. In the yard?

Mr. LIDDLE. Yeah. There is you are going to use very little fuel, so your major cost items will be the other items, and that tends to go against the coal-fired locomotive in that type of service.

However, on the long haul, then you would be using a lot of fuel, and there is the advantage of coal. So there is a tradeoff, and this depends on the railroad involved. A shortrun railroad I think would have problems justifying a coal-fired locomotive.

Senator WARNER. But those systems that transport long distances, particularly substantial grades—I received a Christmas card with a scene of a diesel coming up over the Donner Pass, which is one of the larger grades on the rail system; that would benefit from use of coal.

Mr. LIDDLE. Yes, very definitely.

Senator WARNER. You mentioned you thought more research was needed in the aseas of coal combustion, remote control, logistics, and engines. Would you expand on that?

Mr. LIDDLE. First, the remote control. To the best of my knowledge no one has a mobile remote-control coal-combustion system, and we have to fit it in the needs of the railroad in operation.

So we need to find out how to control these combustion systems and the engine that goes with them by total remote operation so we know how to run that locomotive to do anything in case something goes wrong. We have to learn how to do that.

Senator WARNER. That is technically achievable?

Mr. LIDDLE. Yes.

Senator WARNER. I visited the Morgantown Center, which is the Federal Center just across the border of Virginia into West Virginia where they are doing research on the various coal fuels—I should say the various fuels with the principal one being coal.

Have you had the benefit of their research?

Mr. LIDDLE. Yes, I've been over there.

Senator WARNER. I think they are doing an outstanding job.

Mr. LIDDLE. I have talked to them. What they have been doing may not be directly applicable to the locomotive. The science of the locomotive is quite different than that of the utilities, so there are going to have to be some adaptations made. A lot of what they have done already I think is very applicable.

Senator WARNER. A lot of this study has been for pulverized coal where they have it as fine as talcum powder and they can sort of fluidize it in several ways.

On page 23 of your study you make this statement:

> In the future, railroads will probably use more than one fuel in their fleet of locomotives. The use of one fuel in the past was convenient and economical, but now, economics and supply problems dictate a multi-fuel future.

Could you elaborate on that?

Mr. LIDDLE. Looking at the possibility, there are two ways. We are going to use alternative fuels in your diesel engine. Canadians have been doing this for years using a synfuel from the tar sand,

and very little sulfur. Some of the railroads have to use fuels other than diesel. So there are alternatives right there. The other one is the use of a completely different fuel. Some people have proposed methanol.

I would see the railroads introducing some diesel locomotives and some coal.

Senator **Warner**. In my own study of the research and development I learned you can't take liquidized coal and inject it into the existing type of diesel locomotive for the reason that it contains a percentage of ash which will eventually wear out the pistons in the engine. Would you comment on that. How can we liquidize coal today and inject it into the present diesel system if at all?

Mr. **Liddle**. Ash is usually oxide or sulfur oxide which draws on steel and scrape the surface. There is a possibility if you have adiabatic you can do that. In that case you have ash, or something of this nature which is harder than the ash, and then it won't burn out.

As I say, the ceramic engines, the adiabatic diesels are still in the future, but there is a possibility there.

The other thing is to take the coal and remove the ash before putting it in the engine. There are some ways of doing that. They are, however, at considerable cost.

Senator **Warner**. Thank you very much. Will you be able to stay with us?

Mr. **Liddle**. Yes.

Senator **Warner**. We appreciate that.

Now we will hear from Joseph Lema, of the National Coal Association, which represents the Nation's coal-burning industry which certainly offers a unique perspective on this issue. Coal is one of the major commodities hauled by the Nation's railroads. Lowered fuel costs means lower shipping costs, and thus the National Coal Association, as a railroad customer, has an interest in the railroads burning the most competitive fuel possible.

STATEMENT OF JOSEPH E. LEMA, VICE PRESIDENT, TRANSPORTATION, NATIONAL COAL ASSOCIATION

Mr. **Lema**. Thank you, Mr. Chairman. My name is Joseph E. Lema. I am vice president—transportation, of the National Coal Association. Thank you for inviting NCA to testify today. The association represents coal producers, coal sellers, and other organizations associated with America's coal industry.

Our president could not be here today because he is out of the city. However, he wished to convey to you his personal gratitude for having this important hearing.

You and the subcommittee have shown great leadership with regard to the use of America's abundant energy source, coal. The coal industry does warmly appreciate the leadership and holding the recent hearings on coal exports, as well as the current hearings on locomotive power generated by coal.

In summary of my testimony, Mr. Chairman, I will focus on three observations. They are the coal-fired, new coal-fired railroad locomotive power can be good for coal, can be good for coal producers as well as mine workers. It can provide employment and greater utilization of our product. Not only can coal-fired power for railroads be good for coal, it can be good for the railroads themselves because certainly you've heard earlier testimony by experts that it substantially reduces cost to the benefit of the railroad companies themselves.

Third, coal-fired power can be good for the public. It can be good for the public, particularly in lower rates for electricity since the use of the coal-fired locomotives can exist at the price of coal, and coal does now represent more than 50 percent of the fuel used to generate electricity in this Nation. We think by the early 1990's it will be as much as 60 percent of fuel used to generate electric power.

It can be good to lower cost of manufacturers and greater competitiveness of America's manufacturers due to diminished cost of energy used to produce goods and certainly it shows that it lowers substantially the price of coal to our coastal ports, and thereby capture a greater share of the world market for coal.

The use of new technology applies to firing locomotives with coal does stand to be substantially beneficial for the coal, the railroads and for the public.

The coal and railroads do have a long history of mutual participating in furnishing energy to generate electricity, for industrial applications and for exporting overseas markets.

As you know, Mr. Chairman, in earlier decades, coal was the principal source of energy for motor power used in both railroad and water transportation. Coal-fired transportation service did end many years ago as boiler-fired systems came into common use. The possibility of utilizing coal again in surface freight transportation operations appear to be feasible in light of highly favorable economics associated with using coal in comparison to petroleum as a source of energy.

I think, Mr. Chairman, you referred to rather long trains and your recent photograph that showed a long train moving through Donner Pass. It is clear that coal is important to the railroads, and that coal unit trains, all 100 to 150 cars in length, are powered by 5 to 7 locomotives are a very interesting possibility with regard to the use of coal itself, not only for the private carrier, but also for the fuel use carrier.

So with the unique application possible to power the unit trains, which now carry on the order of 55 percent of all coal moved by railroads, the unit trains are in increasing use, and obviously if they collect coal for delivery, they then collect coal for burning in the locomotive as well.

I would like to draw a comparison in economics. It is not perfectly suited to use of coal versus petroleum as a source of energy for electric power. Nonetheless, it is indicative of potential price advantage that coal enjoys.

In terms of dollars per million Btu's, the price of oil was higher by more than a factor of 2.5, compared to the price of steam coal delivered to electric utilities in the first quarter of this year. Obviously there are some differences when you are examining the possibility of coal for rail locomotive power versus generating electric power. Nonetheless, the price advantage is a very good signal for what we might get in transportation savings by using coal.

Coal is our Nation's abundant energy resource. It represents more than 80 percent of America's reserves in energy, with about 470 billion tons of coal potentially mineable in the United States with current technology.

Coal production of coal last year was 834 million tons in the United States. National Coal Association now estimates there will be a drop in production in 1983 down from 834 million tons last year to about 780 million tons this year. However, we do forecast some recovery to about 816 million tons in 1984.

However, notwithstanding the fact that we are producing on the order of 825 million tons per year, the coal industry believes if we were mining facilities now in place, we actually could produce about 1 billion tons of coal this year if we had the market.

Likewise, we have the work force readily available to produce much more coal. About one-third of our Nation's mineworkers in the coal industry are unemployed, and in some places mineworker unemployment, particularly some counties in West Virginia is especially serious where 50 percent or more of the work force are unemployed.

Senator WARNER. That's not only mineworkers, but a lot of other people associated with the coal industry.

Mr. LEMA. Yes; I would say the community around the mines suffer greatly by unemployment and it carries forward to many other businesses.

Senator WARNER. I make frequent visits to the mines in West Virginia as well as Virginia. I can assure you it's a very distressful sight to see those able-bodied men in the need of work.

What is your current estimate this Christmas on the number of miners out of work?

Mr. LEMA. Certainly on a national scale it will be 40 percent of the available mineworker workforce.

Senator WARNER. That's how many individuals?

Mr. LEMA. That would be on the order of—I would say individual mineworker unemployment would be on the order of 20,000 to 30,000.

There are some mineworker possibilities when it comes to Western coal—if in their markets for other minerals they would switch. In any event, it is a very tragic circumstance.

Senator WARNER. So just mines alone is around 30,000?

Mr. LEMA. Yes.

Mr. Chairman, although America is rich in coal reserves, and we certainly are, we see substantial underutilization of our coal mining capacity, even though coal has a price advantage. Obviously it is in the public interest to see greater use of America's coal for generating electricity, for fuel and industry, for exportation to other world energy markets.

Of course, when you lose coal exports, you also lose employment in great ports that we have. As the subcommittee now has under consideration the use of coal to fuel our Nation's railroad transportation system, as earlier witnesses have testified, we recently have found we use the coal for fuel in coastal vessels in New England electric system's newly dedicated coal-fired collier.

We also have other prospective maritime uses of coal for transportation service which are being examined. We believe it is most appropriate for this subcommittee to encourage similar returns of coal for fueling railroad locomotives. We believe that state-of-the-art technology in its most advanced form can be applied effectively in design and operating locomotives with motor power by coal.

I can assure you that it is a high interest to the coal industry that the railroad industry, through some recent announcements, is seriously investigating a move to the new coal-fired locomotive power. Many of those announcements being an Eastern railroad headquartered in Virginia.

We do need efficient and reasonably priced freight transportation services to enable full and complete utilization of America's coal. NCA forecasts our national coal production in the United States to increase from 834 million tons in 1982, last year, up to 940 million tons by 1990, and up to 1.12 billion tons annually by 1995. We have had other hopes, but those hopes have been somewhat quashed by a rather slow move to greater use of coal. Moving from 834 million tons in 1982 to in 12 or 13 years to 1.12 billion tons is a substantial increase.

Eastern's coal production forecast would increase annually 1½ percent. The Western coal production is forecast to increase annually at 3.8 percent. In 1982 Eastern coal's share of total coal production was 67 percent; whereas by 1995 Eastern coal's share will be about 60 percent.

We are confident that our coal production capacity will remain well ahead of coal demands for 1990, and we believe that our railroads and river transportation networks likewise will be well prepared to meet the demand for coal transportation services. In fact, the Association of American Railroads, and I hope they are present in the audience, have reported that at least 20 percent of the railroad's industry present capacity for moving coal is not being utilized. Therefore, American's river system and its railroad system which haul coal are both clearly operating well below their capacities. Coal production and consumption are constrained simply by market demand and are not limited by insufficient capacity. Thus, new uses for coal in the railroad transportation systems are much to be desired.

Moreover, it is imperative that to reach the complete utilization of America's coal in competition with other sources of energy, both domestic and foreign, coal delivered price must be reasonable. Transportation now accounts for 25 to 50 percent of coal's delivered price in the United States today, and for some coal shipments, as much as 70 percent.

Thus, we must take meaningful steps to hold down transportation costs. From 1976 to 1981, at the same time the coal prices at the mine declined by 18 percent, railroad rates charged traffic dollars increased by 40 percent. This is of some concern about the direction in which railroad coal transportation rates are moving and its affect on delivered price coal.

About 65 percent of coal tonnage is carried by the railroads, and according to our studies, 85 percent of that railroad coal tonnage has more effective transportation option. It must be moved by the railroad, and most often by one railroad serving the mine. We must have efficient and reasonably priced railroad transportation services for moving coal.

Fuel costs are a major element of the overall cost of providing freight transportation services. To the extent that coal can be used more economically than petroleum to fuel railroad locomotives, the cost of providing transportation service are reduced materially, a factor that should result in lower railroad coal freight rates, should result in lower railroad coal freight rates, giving that the savings are passed on by the rail carriers and the coal shippers.

Thus, the delivered price of coal is less and coal will obtain its highest and best use in various markets. This does mean, as I indicated in the outset, lower cost for electricity, lower cost of energy used in industry, and lower prices for coal exported overseas. All of these factors will go greatly to the consumers and to the economy of our Nation.

These possibilities are good for the public and good for the railroads. Moving more coal traffic at reduced costs clearly is a worthwhile move for the railroad. In 1982, coal was 41 percent of total railroad freight tonnage, four times as much as any other commodity, and amounted to 30 percent of all railroad car loadings, and contributed 25 percent of total railroad revenues.

Interestingly enough, according to the electric utility industry, the Edison Electric Institute shows that profits derived by the railroads from coal on a first-time basis are 75 percent higher than profits derived from hauling available freight. So clearly coal traffic is desirable.

The railroads in 1982 utilized $6.3 billion in revenues for moving 524 million tons of coal. You indicated in your opening statement, Mr. Chairman, that billions of dollars—billions of gallons of gasoline—or petroleum, are employed in providing railroad transportation service and the price is about $1 a gallon now. Of course, it will always be used.

Certainly this constitutes an important opportunity for greater utilization of America's coal. Fuel and power costs are about 11½ percent of the railroad's total expenses including taxes last year.

The fuel used, of course, is petroleum. A new initiative toward coal usage can have highly beneficial implications.

Mr. Chairman, the coal industry must admit that lately the Congress has heard much testimony from us about recent failures, in our view, of the Interstate Commerce Commission in providing balanced regulation of the railroads. Regulations should not only be sensitive to the rail carriers to obtain adequate revenues, but we surely hope the Commission fully exhibits that tendency, but also should be effective in keeping rail rates charged captive shippers reasonable, an objective the Commission ignores. Perhaps the Commission, working in concert with the Departments of Transportation and Energy, should be asked to focus greater attention to ways for reducing railroad costs in its drive toward assuring that rail carriers are healthy—and, at the same time, to aim at passing the benefits of reduced costs on to shippers and the public as efficiencies are improved. This could be accomplished, for instance, by establishing up-to-date information with information readily retrievable which could be utilized to help private sector—to promote private sector investment in a new coal-fired railroad locomotive operation.

In closing, Mr. Chairman, we believe that the railroads, especially the major coal-carrying railroad system, now are financially healthy and are well positioned to implement new coal-fired locomotive technology with their own resources by reinvesting some of their revenues to improve the efficiency of the railroad business.

We urge this subcommittee to encourage such development, a step which holds much promise for more efficient, less costly service; one that, we believe, is substantially in the public interest. Thank you for allowing me to appear before this subcommittee hearing, Mr. Chairman. I will be glad to respond to any questions.

Senator **Warner**. Thank you.

[The prepared statement of Mr. Lema follows:]

STATEMENT OF JOSEPH E. LEMA
VICE PRESIDENT - TRANSPORTATION
NATIONAL COAL ASSOCIATION,
ON REINTRODUCTION OF COAL
AS FUEL FOR RAILROAD LOCOMOTIVES,
BEFORE THE SUBCOMMITTEE ON
ENERGY AND MINERAL RESOURCES
UNITED STATES SENATE, ON
DECEMBER 20, 1983 -- WASHINGTON, D.C.

Mr. Chairman, my name is Joseph E. Lema. I am Vice President--Transportation of the National Coal Association. NCA represents coal producers, coal sellers, and other organizations associated with America's coal industry.

We commend you, Mr. Chairman, for holding hearings on the reintroduction of coal as fuel for railroad locomotives.

Coal and the railroads have a long history of mutual participation in furnishing energy for generating electricity, for industrial applications, and for export to overseas markets. As you know, in earlier decades coal was the principal source of energy for motive power utilized in railroad and water transportation systems.

Although the previous era of coal-fired transportation service ended many years ago as oil-fired systems came into common use, the possibility of utilizing coal again in long-haul surface freight transportation operations appears to be feasible in light of highly favorable economics associated with using coal in comparison with petroleum as a source of energy. For example, although this comparison is not totally suited to coal versus petroleum as a source of energy for transportation, it is indicative of the potential price advantage which thus could be realized by examining the prices of fuel utilized in electric utility plants. In terms of dollars per million BTUs the price of oil was higher by a factor of more than 2.5 compared with the price of steam coal delivered to electric utilities in the first quarter of 1983. Obviously, there are some differences which must be accounted for when looking at coal versus petroleum for generating electricity and for providing motive power for railroad locomotives. Nonetheless, it is clear that coal's price advantages and the security of supply enjoyed by America's coal in contrast with unstable foreign oil sources are clearly important in assessing the likelihood of utilizing coal in fueling railroad transportation systems.

Coal is our nation's abundant energy source, representing more than 80 percent of America's reserves, with about 470 billion tons of coal potentially minable in the U.S. using current technology. Total production of coal in the U.S. last year was 834 million tons. NCA estimates a drop in production down to 780 million tons this year, and forecasts recovery upward to 816 million tons in 1984. However, we believe that with mining facilities now in place we already could produce one billion tons yearly. Likewise we have the work force readily available to produce much more coal. About one-third of our nation's mineworkers in the coal industry are unemployed, and in some places coal mineworker unemployment is especially serious with 50 percent or more of the work force unemployed.

So, Mr. Chairman, although America is blessed with rich and plentiful coal reserves, we see substantial under-utilization of our coal mining capacity today, even though coal has a price advantage. Obviously it is in the public interest to seek greater use of America's coal for generating electricity, for fueling industry, for exportation to other world energy markets, and as this Subcommittee now has under consideration, for fueling our nation's railroad transportation systems. We recently have witnessed a return to coal for fueling coastal vessel~~s in~~ New England Electric System's newly dedicated coal-fired collier. Other prospective maritime uses of coal for transportation service also are being examined. It is most appropriate to encourage similar returns to coal for fueling railroad locomotives. We believe that state-of-the-art technology in its most advanced form, can be applied effectively toward designing and operating railroad locomotives whose motive power is delivered by coal. It is of high interest to the coal industry that the railroad industry, through some recent announcements is seriously investigating a move into new coal-fired locomotive power.

We need efficient and reasonable priced freight transportation services to enable full and complete utilization of America's coal. NCA forecasts annual coal production in the U.S. to increase from 834 million tons in 1982 to 940 million tons by 1990 and to 1.12 billion tons by 1995. Eastern coal production is forecast to increase annually at 1.5 percent and

Western coal production is forecast to increase annually at 3.8 percent. In 1982 Eastern coal's share of total coal production was 67 percent, and by 1995 Eastern coal's share is forecast at about 60 percent.

We are confident that our coal production capacity will remain well ahead of coal demand into the 1990s and we believe that our railroad and river transportation networks likewise will be well prepared to meet the demand for coal transportation services. In fact, the Association of American Railroads has reported that at least 20 percent of the railroad industry's present capacity for moving coal is not now being utilized. Therefore, America's coal supply and delivery systems clearly are operating well below their capacities, coal production and consumption are constrained simply by market demand and are not limited through insufficent capacity. Thus, new uses for coal in fueling transportation systems, railroads and water carriers, are much to be desired.

Moreover, it is imperative that to reach full and complete utilization of America's coal in competition with other sources of energy, domestic and foreign, coal's delivered price must be reasonable. Transportation now accounts for 25 to 50 percent of coal's total delivered price in the U.S. today, and for some coal shipments as much as 70 percent. Thus, we must take meaningful steps to hold down transportation costs. From 1976 to 1981, at the same time that coal prices at the mine declined by 18 percent, railroad rates charged coal traffic increased by 40 percent, and these figures are stated in constant dollars.

About 65 percent of total coal tonnage is carried by the railroads, and according to NCA studies, 85 percent of the railroad coal tonnage has no effective transportation option available. We must have efficient and reasonably priced railroad transportation services for moving coal. Fuel costs are a major element of the overall costs of providing freight transportation services. To the extent that coal can be used more economically than petroleum to fuel railroad locomotives, the costs of providing service are reduced materially, a factor that should result in lower railroad coal freight rates given that savings are passed on by rail carriers to coal shippers. Thus, the delivered price of coal is less and coal will attain its highest and best use in various markets. This means lower costs of electricity, lower costs of energy used in industry, and lower prices of coal for export overseas, all of which will inure greatly to consumers and the economy of our nation.

These possibilities are not only good for coal and good for the public, but also they are good for the railroads. Moving more coal traffic at reduced costs clearly is a worthwhile goal for the railroads. In 1982 coal was 41 percent of total railroad freight tonnage originated by all Class I rail carriers, and amounted to more than 30 percent of all railroad carloadings and 24 percent of total railroad revenues. According to the Edison Electric Institute railroad profits derived from coal movements on a per-ton basis are 75 percent higher than for all railroad freight.

The railroads, in 1982, realized $6.3 billion in revenues for moving 524 million tons of coal. Obviously, coal is well suited to movements by railroad, representing the railroads leading commodity, and coal needs a healthy well-managed railroad freight network.

In 1982 the railroads consumed 3.2 billion gallons of petroleum costing $3.1 billion, about one dollar per gallon, in providing freight service; and, of course, no coal was used. Certainly this constitutes an important target of opportunity for greater utilization of America's coal. Fuel and motive power costs were 11.5 percent of the railroads' total expenses including taxes last year. The fuel used, as we know, was petroleum. A new initiative toward coal usage can have highly beneficial implications in regard to the budget for railroad freight transportation services required for moving coal and many other bulk commodities and heavy goods essential to our commerce, industry and national defense. Now is the time to stimulate new uses of coal in furnishing less costly and more reasonably priced railroad transportation.

Mr. Chairman, lately the Congress has heard much in testimony from the coal industry about recent failures of the Interstate Commerce Commission in providing balanced regulation of the railroads--regulation which not only should be sensitive to enabling rail carriers to obtain adequate revenues, as the Commission fully exhibits; but also must be effective in keeping rail rates charged captive shippers reasonable, an objective the Commission ignores. Perhaps the Commission, working in concert with the Departments of Transportation and of Energy, should be asked to focus greater attention to ways for reducing railroad costs in its drive toward assuring that rail carriers are healthy--and, at the same time, to aim at passing the benefits of reduced costs on to shippers and the public as efficiencies are improved. In closing, Mr. Chairman, we believe that the railroads, especially the major coal-carrying railroad systems, now are financially healthy and are well-positioned to implement new coal-fired locomotive technology with their own resources. We urge this Subcommittee to encourage such development, a step which holds much promise for more efficient, less costly service; one that, we believe, is substantially in the public interest. Thank you for allowing me to appear before this Subcommittee hearing, Mr. Chairman. I will be glad to respond to your questions.

Senator **Warner**. This subcommittee, indeed with several other subcommittees of the Senate, are looking at legislation providing for ports in the United States to deepen their channels to accommodate super coal colliers. We are talking about substantial sums of money. The legislation has not as yet gone to the floor. The issue is primarily what percentage will be borne by the overall American taxpayer in terms of Federal funds, whether or not the cost should be borne by the local taxpayers.

In any event, it takes big dollars to dredge these ports, but we've got to do it for the reason that other nations like Canada and Australia are coal export competitors who have improved their port facilities. In fact, they are taking the business away from this country; is that correct?

Mr. **Lema**. Mr. Chairman, that is correct. The coal industry strongly supports enactment of legislation in this session that would, in fact, allow for this at selected ports. We do not, per se, oppose user fees. User fees have a place as long as there is a balance between user charges and the benefit to the public in general. We need to accommodate 150,000 to 200,000 dead-weight ton vessels.

Senator **Warner**. Let's assume this is the port and this is the coal mine, and if the American taxpayer, through several types of financing, are going to put dollars into this movement, the mines now you say are 50 percent operating and 40 percent down, and in between is the rail system, and anything we can do to reduce this cost between those two points will better enable the United States of America to justify a substantial investment in coal improvement and eventually go back to where coal miners can be competitive. We have a serious balance-of-payment problem.

Mr. LEMA. We agree with that. We might note for the record that coal producers in the last 2 or 3 years have made substantial investments in new ground site facilities.

Senator WARNER. Back here at this end.

Mr. LEMA. At the mine as well as in the harbor area, Newport News, Hampton Roads, and these investments have been made by private industry, largely coal producers. We believe that similar investments by the railroads allowing more efficient connection from the mines to the ports is much in order.

Senator WARNER. Coal is one of America's major export commodities. We have some of the finest and best coal to be found anywhere.

So we can improve this link crosswise in the coming years, it will not only justify the investments here, the investment at the coal mines, but put America back in a better trading position.

Gentlemen, you have been patient. We will go in the same order you were first called. Do you have any further comment?

Mr. WITHUHN. I have one thought, Senator Warner, on how widely coal could be used throughout the rail industry, not only in the East but the West and all the contiguous States. That would have to do with a new way of packaging the coal and handling it. My own observation is that the transition from the old style steam locomotive to the diesels occurred because of rail rates return around 8 percent.

When we look at the potential investment return that is available when you make the switch in reverse from diesel back to coal, even with the least efficient locomotive and using the most expensive coal, the real rates of return are on the order 20, 30, 40 percent, of course all predicated on the taxable.

It seems to me that that kind of economic pressure, once it's demonstrated as a practical device, is going to do the same kind of thing that happened in the 1940's and 1950's. The change got started because of an 8 percent railroad return. It happened because of the economics, and I think along with those economics, most pressure would come from the study of infrastructure. How do you handle packaged coal so you don't have to process it? So to package it in such a way that the system could handle it throughout the railroad system and elsewhere.

Dr. Liddle mentioned the results might not be the same. It seems to me I would like to turn the key on, crank up the locomotive, go about my business and shut it down, and if it was a convenient and easy thing to use, I certainly would invest.

Senator WARNER. Mr. Liddle?

Mr. LIDDLE. I agree with Bill. We need to have some research on the logisitics. What Bill is talking about is exactly that. The logistics depends on what type coal you are using in the locomotive, whether its granular coal used in fluidized bed, or highly powdered coal in direct-fired gas turbine, or whether it's a coal gasification system. The problem is there are lots of ways of using the coal, and the one thing that I haven't seen so far is the one thing that JPL has been very interested in is trying to assess which kind of coal combustion system in what engine would be the best suited to this particular application. We can't depend on the research that has been done. It has to be done for this particular job, and it has to be done in cooperation with the railroads, because they are going to live with it. It has to be done with Government because of the environmental impacts involved, and it's got to be done with such community in the United States. We think there is a good mix for the possibility of the coal-fired locomotive as well. .

So it's not just for us in getting help with the exports, not only for the export of coal, but for the export of locomotives themselves.

Senator WARNER. I'm delighted you brought that point up because my own research shows that there are two principal producers of diesel locomotives in the United States—General Motors and General Electric—and that they are major exporters of those engines all over the world.

If we can pursuasively convince the Americans to manaufacturer a locomotive fueled by coal, indeed the economic benefits present in the United States from using such locomotive would be present also abroad, which, in some instances might be stronger because of the increased cost of coal in the countries that don't have it. In addition to exporting the coal, we can export the engines.

Mr. LIDDLE. I think the thing we need at this time is a prototype locomotive that we can use as a research tool to find out just what has to be done.

Senator WARNER. That is why this chairman of this subcommittee and other Members of the Senate working with me are excited about this project. And we wanted to afford the experts who have done a lot of research to provide testimony for the record here in the Senate.

As you know, I am also on the Senate Armed Services Committee, and we spend billions and billions of dollars, justifiably, on national defense problems. It seems to me we are going to have to find a way to have a small sum of money, in the area of $50 to $70 million over a period of 5 years to build a prototype, maybe two prototypes, of coal-fired loacomotives.

The number of prototypes has to be decided by those who are far more a technical expert than I. What I want to do in this subcommittee is to provide the record for the Senate and then see if collectively we can't make a judgment that there is sufficient reason to believe that this can be done technically, economically, and we do it.

I have offered anyone who has an interest in this subject to come forward. I am pleased that you have come forward today. Others will come forward on January 9 when we have to complete the record.

I would like to say that not one person has stepped up to say that this idea won't work, and that it's a pie in the sky. To that extent, I think we've had success.

Again, there are copies of testimony available for those who have requested the testimony.

If there is no further desire on the part of anyone to provide testimony, this hearing is closed. The subcommittee will reconvene on January 9 in Richmond, VA.

[Whereupon, at 11:20 a.m., the hearing was recessed, to reconvene January 9, 1984.]

COAL USE BY THE NATION'S RAILROADS

THURSDAY, JANUARY 19, 1984

U.S. SENATE,
SUBCOMMITTEE ON ENERGY AND MINERAL RESOURCES,
COMMITTEE ON ENERGY AND NATURAL RESOURCES,
Richmond, VA.

The subcommittee met, pursuant to notice, at 9:30 a.m., in the 4th floor courtroom, U.S. Court of Appeals Building, 10th and Main Streets, Hon. John W. Warner presiding.

Present: Senator Warner.

Also present: Roger Sindelar, counsel.

OPENING STATEMENT OF HON. JOHN W. WARNER, A U.S. SENATOR FROM THE STATE OF VIRGINIA

Senator WARNER. The Senate Subcommittee on Energy and Mineral Resources convenes this morning for the third in a series of hearings on the potential for reintroduction of coal as fuel for railroad locomotives.

Witnesses at the November 28 hearing in Roanoke and the December 20 hearing in Washington, DC told the subcommittee that in approximately 5 years the United States could be burning fuel derived from coal in railroad locomotives. I want the Congress to accept this challenge as a high priority in America's move toward freeing ourselves from imported oil.

I intend to pursue it until either coal is being burned in railroad locomotives or I am convinced that it simply is not economically feasible. We all have an obligation to the thousands of unemployed coal miners and railroad workers not to raise false hopes, but to pursue diligently this new technology so that we can accurately assess its true potential.

The subcommittee is seeking additional testimony on several aspects of using coal in locomotives: For example, the current status of research and demonstration projects; the outlook for this new technology; drawbacks and problems with coal-burning locomotives; what, if any, is the appropriate role of the Federal Government in encouraging industry to use railroad locomotives burning coal; the importance of the Nation's railroads to the movement of essential goods and personnel and to our national defense; and how the railroads—which are now totally dependent on diesel fuel—would continue to be operated in the event of an oil supply disruption.

Today, some 40,000 U.S. railroad locomotives burn approximately 800,000 gallons daily or 4 billion gallons annually of diesel fuel. With diesel fuel costing around $1 a gallon, this puts America's rail fuel bill at nearly $4 billion. The challenge to America, in both the

Federal Government and private industry, is to explore reintroducing coal as the fuel for railroad locomotives.

Preliminary estimates indicate that reconversion of all the Nation's locomotives to coal would lower fuel costs by as much as 50 percent. Lower transportation costs could increase coal sales for the depressed coal industry by at least 20 million tons.

This means more competitive transportation rates, lower costs of goods to consumers, and thousands of jobs for U.S. coal miners. Greater use of rail transportation because of lower fuel costs should also increase rail employment.

My recent fact-finding trip to the Middle East has reinforced my deep concern about the vulnerability of the United States to an oil supply disruption. More than one-third of the oil consumed in the United States continues to be imported. One-third of the crude oil sold in the international market today passes in oil tankers through the Straits of Hormuz which is only minutes by fighter planes from war-torn Iran and Iraq. The closing of the Straits of Hormuz means the immediate withdrawal of 10 million barrels per day of international oil supplies.

Railroads are the lifeblood of our economy, transporting goods to every corner of the United States. The rail system is a part of the foundation of our country's national defense. In times of national emergency, the United States is even more dependent on our railroad transportation system.

In 1981, diesel fuel burned by railroads represented 12.4 percent of total U.S. consumption of OPEC oil. Because of the possibility of interruption of foreign oil supplies during national emergencies, the dependence of our national railroad system on imports of OPEC oil must be removed. The burning of coal by locomotives would reduce oil imports and make available supplies of diesel fuel for other national needs. This is vitally important to our Nation's economy, energy independence, and national security.

This morning, we have a distinguished panel of witnesses who are well-qualified to testify on restoring fuel derived from coal to railroad locomotives. I welcome all the witnesses and look forward to their testimony.

STATEMENT OF JACK R. McCRADY, JR., LEGISLATIVE REPRESENTATIVE, UNITED MINE WORKERS OF AMERICA, WASHINGTON, DC

Mr. McCRADY. Mr. Chairman and members of the committee. My Name is Jack McCrady and I am a legislative representative for the United Mine Workers of America and an underground coal miner from district 28 in Virginia.

On behalf of the UMWA we would like to thank the chairman and the committee for holding these important hearings. We would further like to applaud the concern the committee has shown for the development of coal markets and the need for technology for the use of coal.

The United Mine Workers is composed of approximately one-quarter million working, retired, and unemployed coal miners throughout the United States and Canada. While our membership is heaviest in the coal mining communities east of the Mississippi

River, we represent thousands of underground and surface coal miners in Western States, including Arkansas, Oklahoma, Kansas, Missouri, Arizona, New Mexico, Colorado, Utah, Wyoming, Montana, and North Dakota. All told, we represent approximately 70 percent of the U.S. workers.

Coal has provided the energy for America's social and industrial progress. Throughout the first half of this century, coal and coal miners provided the backbone of American industrial might. Coal provided heat and electricity to homes, businesses and factories and powered transoceanic ships and transcontinental railroads.

In the last 30 years, however, coal has been subordinated to petroleum and natural gas as an energy source, and substantial Federal resources have been allotted to the development of nuclear power. The UMWA believes that the energy policies of the last 30 years have weakened our economy and threatened our national security. To regain energy independence and economic strength, the United States must adopt energy and economic policies that rest squarely on coal.

Coal is the United States' most abundant energy resource. With about one-third of the world's coal reserves, we have enough coal to last approximately 400 years at current levels. Existing production and transportation networks, together with a highly skilled workforce, make the U.S. coal industry a reliable supplier of energy both domestically and abroad. In terms of cost, coal holds a significant advantage over competing fuels. For example, the average cost, on a Btu basis, of natural gas delivered to powerplants in 1981 was nearly twice that of coal while the average cost of oil was three and a half times greater than coal.

These figures clearly show the economic advantage of establishing a coal-based economy, but there are other important reasons to increase our reliance on domestic coal. Each year the United States spends more than $80 billion to purchase foreign oil. This is $80 billion that leaves our domestic economy to provide jobs and capital abroad. Although the oil prices have declined somewhat, the United States remains energy vulnerable—and therefore, economically vulnerable. An oil embargo by OPEC could occur at any time; war in the Middle East could disrupt fragile supply lines. The United States can ill afford to gamble its future on the false hope that foreign oil prices and supplies will remain stable. The United States must act now to ensure energy independence.

Formulating an energy policy with coal as its centerpiece requires a comprehensive review of the coal cycle from production to end use. The various elements cannot be viewed in isolation; a major problem in transportation, production, consumption, in regulatory or tax policy can impede the development and growth of our coal industry. Coherent policies can allow us to achieve our goal of energy security, help revitalize our industrial heartland and create jobs in all sectors of the economy.

Mr. Chairman, that is why these hearings are so important. The hearings focus on two major policy issues. The utilization of coal and building of an efficient and competitive transportation system.

There are at present approximately 60,000 highly skilled UMWA coal miners who are unemployed. These coal miners stand ready, as they have so often in the past, to provide this Nation with its energy—to lead the Nation to energy independence. In 1981, about 12.4 percent—a considerable percentage—of imported oil was used to power our Nation's railroads. That imported oil cost our country almost $10 billion. It is clear that a conversion of railroad locomotives from diesel fuel to coal could save this Nation billions of dollars while moving our Nation toward energy independence. It is further estimated that the conversion would create a market for approximately 50 million tons of coal. This would be important to laid-off miners in America.

In addition to paring the trade deficit and creating jobs for miners, it is simply good public policy and good transportation policy. If the conversion from diesel fuel to coal was made U.S. railroads could cut their fuel bill by half, and cut their overall locomotive costs by at least half according to Mr. William L. Withuhn, consultant on railroad economics and operations. That is extremely important when one considers that transportation now accounts for 25 to 50 percent of coal's total delivered price in the United States today, and for some coal shipments as much as 70 percent. Since fuel costs are a major element of the overall costs of providing freight transportation services, a major reduction in fuel costs should serve to moderate rail rates. This will not only be important for coal, it will be important for all freight transported by rail.

In addition, if we can deliver our coal to the marketplace at lower costs it will not only lower the cost of electricity both for home heating and industry, but will aid in rebuilding our declining export market.

Mr. Chairman, the UMWA wholeheartedly supports and encourages the committee to take the steps necessary to make the conversion from diesel fuel to coal in our Nation's railroads. The UMWA believes sincerely that it is simply good public policy. I certainly thank you, sir.

Senator WARNER. Mr. McCrady, we thank you for joining us this morning. I've had the pleasure of working with your President and I think its in the best interests of this Nation that the UMWA now has a strong voice in policy matters and the direction it goes. Today, I would like to share an article relating to the potential further loss of the export market of coal. Would you care to comment on that article, or perhaps you've not had a chance to read it.

Mr. MCCRADY. I haven't had the opportunity to read it.

Senator WARNER. But you are aware of the fact?

Mr. MCCRADY. Yes, sir. We are quite aware that the Japanese are opening up their market early this year for the 1984-85 bids on their coal. It seems very unlikely that with the Australian, South African coal, particularly the South African coal, that we can compete on a labor cost basis, if you want to discuss labor costs with anyone concerned. But the transportation cost is why we feel that this conversion program you are discussing is important.

Senator WARNER. I've heard that some mines in South Africa pay as low as $2 a day, is that correct?

Mr. MCCRADY. $2.60 was the figure.

Senator WARNER. For a whole days' labor in the coal mine?

Mr. MCCRADY. Yes, sir.

Senator WARNER. And that's the type of labor cost that you are up against.

Mr. McCrady. One other note on the cost of our markets that we do have. We are all concerned with export markets, and of course coal slurry is a big issue in Virginia today. UMWA is in oppposition to coal slurries. Whereas, on the federal level, we are interested in domestic markets and the conversion of our present oil-fired generators to electricity. We are very concerned with the conversion of present-day plants to the use of coal, coal-fired mixture, along with this program that will add approximately 50 million tons of coal use. That's a lot of jobs. I had a lot of friends and relatives who have been out of work for over 2 years in the coal industry, and these are not newcomers to the coal industry. These are people with 15, 20, and 30 years of mining experience who no longer have a job. We are very concerned with it.

Senator Warner. We thank you for appearing this morning.

Mr. McCrady. Thank you very much.

STATEMENT OF H.W. KITTS, SR., DIRECTOR, VIRGINIA STATE LEGISLATIVE BOARD, UNITED TRANSPORTATION UNION

Mr. Kitts. Thank you, Mr. Chairman, and good morning. I apologize for not having prepared remarks.

Senator Warner. The record will remain open and you, and I have discussed your intention to put in a statement for the record.

Mr. Kitts. Thank you, sir. We will, at a later time, submit more refined remarks. Mr. Chairman, ladies and gentlemen, we too, of the rail labor applaud the steps, the initiatives both by the railroads and by you, Mr. Chairman, as taking the opportune moment and we feel the critical moment in the coal industry and the rail industry to reintroduce coal as the fuel for the railways. Maybe it would, some way, reduce the transportation rates that we hear a lot about. I do think that there is criticism of the railroads, of high profits. I think perhaps this may be the wrong time or place, but there is much said about it. I think we are all charged with the responsibility of remaining solvent, whether we're in private enterprise or Government. But we view this coal as a fuel, as a way to lower the cost, to reduce our balance of trade debts and make this country energy efficient. And we very much applaud the idea, we accept it graciously and welcome it.

I thank you so much for this opportunity.

Senator Warner. Thank you very much, Mr. Kitts. I recognize that you have to depart from here and the record will be available to you and others.

So now we return to the schedule that we had originally proposed, and our first panel of witnesses will be from the Department of Energy. Leading off will be William A. Vaughan, Assistant Secretary for Environmental Protection, Safety, and Emergency Preparedness; Dr. Helmut Merklein, Assistant Secretary for International Affairs; J. Erich Evered, Administrator, Energy Information Administration; and Richard Harrington, Deputy Assistant Secretary for Coal Utilization. The Chair desires that each of the witnesses make a few preliminary remarks and then we'll get into a general discussion. I want to thank you for making it down from Washington, DC, as I do other witnesses who have traveled from quite a distance to join this morning in this hearing. Secretary Vaughan, will you lead off.

STATEMENT OF HON. WILLIAM A. VAUGHAN, ASSISTANT SECRETARY, ENVIRONMENTAL PROTECTION, SAFETY, AND EMERGENCY PREPAREDNESS, DEPARTMENT OF ENERGY

Mr. **Vaughan**. Mr. Chairman, it is indeed a pleasure for me on behalf of the Department of Energy of the Federal Government to be here this morning and participate in this hearing. It is also a personal pleasure to come back to the city in which I was born. I am quite interested as a senior official responsible for emergency prepareness in anything that any American can do to increase the utilization of coal that this country is blessed with a great abundance of. This State is one of the prime sources of that indigenous domestic supply of fuel. For every pound of coal that is burned our dependence on imported oil, of course, is decreased. We think this administration has done much in that regard by realistically treating markets and allowing markets to operate so that coal can compete along with other fuels. I will not take you through a long litany of the forms of deregulation we think this administration has made good on.

I am prepared, sir, to answer questions as to the role of railroads in emergency preparedness and the need for fuel. I certainly endorse the concept of trying to increase the utilization of coal. Thank you.

Senator **Warner**. Thank you, Mr. Secretary. The Chair has a number of questions to propound to the panel. First, we would like to hear any additional comments that Dr. Merklein might make.

STATEMENT OF DR. HELMUT MERKLEIN, ASSISTANT SECRETARY FOR INTERNATIONAL AFFAIRS, DEPARTMENT OF ENERGY

Dr. **Merklein**. Mr. Chairman, I am very glad to be here, as well. My position at the Department of Energy is Assistant Secretary of International Affairs so obviously my role on this panel will be to look toward other countries to see what they have done. For the most part our foreign allies, especially in Europe, and elsewhere as well are more dependent on imported oil than we are and so to them, their need to develop alternative fuels is more urgent than ours. They have gone through a whole array of mechanisms including the indirect use of coal for production of electricity for electric rails. I've prepared specific questions when we get into some detail on those.

Senator **Warner**. Mr. Secretary, just so it will be part of the opening remarks, I recently returned from a trip to the Mideast as chairman of the Senate Armed Services Committee. We visited President Mubarak and King Hussein to make an appraisal primarily for national defense purposes of our present posture in Lebanon including President Gemayel. I left that area having spoken to those well informed individuals with the impression that it could fracture in such a way as to have a major impact on the oil located there which is needed by the world. The United States fortunately has become less dependent on oil from the Middle East by increasing our imports from such areas as Central and South America.

Would you give your appraisal of that part of the world and do you concur in my opinion that it could fracture in such a way in the foreseeable future, in the near foreseeable future, that it could have a major impact on the worldwide energy situation?

Dr. MERKLEIN. Yes., Mr. Chairman, it's true that our dependence on Middle East oil has been lessened in a direct way. The recent bombings in Kuwait brought home the point that the conflict may not be confined to Lebanon. As you well know, there were three Kuwait targets and three non-Kuwait targets. The seventh target was also in Kuwait but the bomb was defused in time. There's a great deal of vulnerability in the Middle East. The truck that unfortunately blew up the marine compound in Lebanon—that same truck in Saudi Abrabia could do considerable damage.

Senator WARNER. It's that type of terrorist vehicle that could be disruptive to any structure that conveys oil?

Dr. MERKLEIN. Yes, there's a great deal of vulnerability there in terms of sabotage. There's a great deal of vulnerability there in terms of direct governmental aggression, and the closing of the Strait of Hormuz. Of course, Assistant Secretary Vaughan is more competent in that area. There has been an increasing awareness of the problem and an attempt to grapple with the crisis should it occur. While it is true that we would not be directly as concerned with the cessation of oil exports from the Middle East, we nevertheless would be very hard hit by either and the international obligations we have, for example, under the International Energy Agency. This, as you well know, is a sort of an international oil import insurance program whereby if allied countries—there are 21 of them, most of them European—are subject to an embargo or to a disruption of oil imports where the triggering factors are set into motion those countries less affected would then be obligated and willing to come to the aid of the countries that are harder hit. So while we are directly not as vulnerable to our commitments under the insurance program there is a great deal of vulnerability left, yes sir.

Senator WARNER. Would destruction in the Mideast of oil and gas production cause a consequential increase in the price of the oil which we have got here at home?

Dr. MERKLEIN. It would indeed, yes. Its very difficult to say how high the price would go. These are conjectures. There are projections. We talk about it a whole lot in the Department of Energy itself. There are forecasts but with no precision as to where exactly the price would go.

Senator WARNER. We should also note for the record the war between Iraq and Iran. We won't try to analyze it here, its very complex. But that, too, poses a potential to sources of energy from the Middle East.

Dr. MERKLEIN. Secretary Hodel, as you know, recently went on a trip to the Middle East and among others talked to Sheik Yamani and asked that very question. And the answer is on the record. Sheik Yamani at the time felt, or perhaps wanted the Secretary to know that it was his feeling, that in one way or another there was considerable likelihood that the tension between Iraq and Iran will escalate and that there was a good possibility that Iran, by way of retaliation to Iraq, would perhaps respond by closing the Strait of

Hormuz. Sheik Yamani, at the time, pointed out that this would be almost in the nature of a suicidal mission for Iran and added that if he were Iranian he would certainly not close the Strait of Hormuz. But he wasted no time in also saying that he was not Iranian. I think he simply wanted to point out to the Secretary that the same exists and that we should be conscious of it and prepared to deal with it.

Senator WARNER. And despite governmental or nongovernmental intervention, there are a number of terrorist organizations with a loose affiliation with governments which could impact the oil industry by a series of events on the transportation system.

Dr. MERKLEIN. Yes, sir, there are. Today they are financed mostly by rather fanatic religiously oriented associations, more than 50 percent of the population of Kuwait is non-Kuwait and even among the non-Kuwait Arabs in Kuwait, there are people who adhere to those organizations. Of course, Iran itself is not an Arab state. The same population ratio is true of other gulf states, notably Saudi Arabia and the United Arab Emirates, and you have a whole such population not identified that could pose a very serious threat.

Senator WARNER. Well, to lift you valuable testimony to the theme of this hearing which is the reintroduction of coal as a fuel for American railroads, this Nation—I speak now of the partnernship between Government and industry—should begin to look at alternatives to make America less dependent on oil. And one of these alternatives is how our railway system can depart perhaps from oil someday through the use of coal. I judge it to be your conclusion that in view of the instability in the Middle East and perhaps other parts of the world, it would be a wise investment for America to look at this one type of alternative fuel for a major consumer fuel in the United States?

Dr. MERKLEIN. The need for an increased use of coal in the United States, as long as it's competitive in the market, is imperative to the growth of this country in the long run and also to the bridging of short term scenarios. There is considerable effort over the entire spectrum of alternative energy source development including the liquefaction of coal. In the United States the commercial development of synfuel has passed from the Department of Energy to the U.S. Synfuels Corporation. While I am not sure that a coal liquefaction commercial size plant is in the planning stage or under construction, the first step namely a plant for the gasification of coal is near completion. In Europe they are using coal indirectly in rail transport by converting the rail system throughout the country to electricity—this may or may not pose great obstacles in this country. I am just not qualified to speak on the subject. I could give you a list of countries with all kinds of efforts that they have undertaken in that area. I leave it to your discretion if you wish to pursue the matter.

Senator WARNER. Thank you, Mr. Secretary.

Mr. Evered.

STATEMENT OF HON. J. ERICH EVERED, ADMINISTRATOR, ENERGY INFORMATION ADMINISTRATION, DEPARTMENT OF ENERGY

Mr. EVERED. Mr. Chairman, it's always a pleasure to appear before you and the subcommittee and I'm happy for this opportunity. As Administrator of the Energy Information Administration, it is my primary responsibility to keep score on energy, that is, to gather the myriad statistics and publish them for use by the Government and the public and private industry. Much has been made of the so-called glut in oil supply. I don't like that term. I prefer to describe the situation as a temporary surplus in deliverable supplies of oil. But the American public should not be confused about the fact that we rely on imports of oil for 30 percent or so of our oil supplies. Although our dependence on Middle East sources has reduced substantially recently, as oil demand goes up and our need for imports increases, the marginal barrel—that is, the extra barrel of supply—is going to come from OPEC, and principally the Middle East. Domestically produced coal already plays an essential role in our energy mix, and any increases we can make in the use of U.S. coal will reduce our need for additional imports of oil. The country needs firm efforts in that direction.

Senator WARNER. And now, Mr. Harrington.

STATEMENT OF HON. RICHARD E. HARRINGTON, DEPUTY ASSISTANT SECRETARY FOR COAL UTILIZATION, ADVANCED CONVERSION AND GASIFICATION, DEPARTMENT OF ENERGY

Mr. HARRINGTON. My name is Dick Harrington. I am representing the Department of Energy, Office of Fossil Energy. Specifically, I have responsibility for the Coal Utilization Program. Our principal area of activity is research and development aimed at enhancing the utilization of coal through either the direct use of coal and through the development of new fuel forms derived from coal in a more efficient and effective way. Much needs to be done. Much progress has been made in the area of research and development to enhance our ability to use coal more effectively and more economically as a substitute for oil and gas. Perhaps one of the most important unions that needs to be forged the union between the industrial sector, including users and suppliers of these technologies and Government in providing much of the fine research and development required to make it possible.

Senator WARNER. Have you or any members of the Department had an opportunity to make any preliminary technical evaluation of the feasibility from an engineering standpoint, of the technical feasibility of having such an operating model or models with the next 5 years?

Mr. HARRINGTON. Sir, if I may break the time question separate from your technical question. The answer to the first question is, Yes. We have taken preliminary looks at the application of conversion technologies such as fluidized bed combustion. We have looked at the use of alternate or new fuel forms such as products of coal liquefaction and products of pyrolysis. The potential certainly exists. The question of timing is an important question. As you know, once the technology is available it becomes a matter of the economies to raise the interest of prospective users and to bring it into the marketplace. Unfortunately, the economics of many of the technologies that have been developed, such as coal liquefaction, are just not an important driver at this time to cause the industry to increase the use of coal as a fuel for railroad locomotives. However, I am sure your belief that the time will come when that margin will be closed. I doubt frankly that it would be within a 5-year period. I believe the answer to the question, "technologically—is that possible?"—is that it is possible to have demonstrated the efficacy of technology at that point. It is a separate question as to the degree of penetration into the marketplace.

Senator WARNER. Many witnesses in previous hearings have said that the cost of the engine and the fuel cost might well be half the cost of diesel fuel. In other words, if you could devise and build a railroad engine that consumed coal you might well have an engine that could operate today at one-half the cost. In other words, 50 cents versus a dollar being used for diesel fuel. Now, that's ½ percent you're saving to me is considerable motivation for the industry to explore this alternative fuel.

Mr. HARRINGTON. Yes, sir, I would agree with that. My comment was with respect to the products of coal liquefaction processes. There are certainly a number of technological options that can be explored. I mentioned fluidized bed combustion. Fluidized bed combustion has the capability of using coal with only a minimum amount of processing. In which case, the cost figure that you have cited over half or even less compared to No. 2 diesel fuel would certainly be a possibility. Another fuel form might well be pulverized coal, which again would be a direct application. In the modified fuel form such as liquefaction and gasification, the costs tend to rise.

Senator WARNER. Let me read into the record here part of my opening statement which I deferred as a courtesy for the witnesses to get away quickly.

Today, some 40,000 U.S. rail locomotives burn approximately 800,000 gallons daily or 4 billion gallons annually of diesel fuel. With diesel fuel costing around $1 a gallon, this puts America's rail fuel bill at nearly $4 billion annually. Therefore the challenge to America, in both the Federal Government and private industry, is to explore reintroducing coal as the fuel alternative for rail locomotives. The $4 billion fuel bill is something that this Nation with the volatility of the world situation and the supply sources to the extent we depend on it and our allies and others, that to me is very strong motivation for this partnership that the Government intends to explore the alternatives.

Now, the means by which its done. There are a number of mechanisms by which the Federal Government can exercise this partnership probability—and I emphasize probability. Do you have suggestions on how this might be funded? Could it be funded through existing grants, loans, or tax incentives now available to the Department of Energy or that might be developed in future legislation? Could you provide the various alternatives by which the Federal Government has, in the past, provided inducement to the private sector to develop a particular technology.

Mr. Harrington. One of the most important roles the Federal Government can play, I believe, is to assist our technical community and our industrial community with the conduct of the research and development that tends to have considerably less near term payoff. I fully appreciate the need for the industrial sector to wisely use their resources and that usually translates into applications that have near term, being perhaps within 5 years or so of payoff. The technologies that we are talking about which, in many cases are at a relatively high level maturity—fluidized bed combustion, for example—starts by necessity at a fairly early level of maturity and involves a rather long and frequently fairly expensive track to get to the point where it can be considered as having economic potential for application to such things as the locomotive. I believe that the major Federal Government responsibility is to assist in the conduct of this research and development and bring it to the point of being able to forge a partnership with the user and supplier. Yes sir. I believe that's one of the major activities that will hasten the availability of that technology and, as I mentioned earlier, represent the focus of the departmental representative of the Department of Energy.

Senator Warner. Thank you. Secretary Vaughan, would you care to comment on the question of the various alternatives available for the Federal Government to stimulate an interest in the private sector?

Mr. Vaughan. I think Mr. Harrington has done a good job of outlining the basic approach, Senator. I think perhaps the most useful thing we can do as the Department of Energy and the other Federal departments that have been represented here, and in some of the other parts of this comprehensive subcommittee hearing that you've run, is to carefully go back to Washington and carefully review the detail of this record and really try to give you an official answer from this department or from the Federal Government. Whether or not that's going to be in conjunction with DOT and DOD is something we should look at. In light of the record and answers to the question, how fast, what are the mechanisms, and that sort of thing. I think that none of us here would be able to do that.

Senator Warner. I accept that.

Mr. Vaughan. Of course, we will need the guidance of our Secretary and whatever other Cabinet members that should be involved. In addition, I think the President, or whoever it may be, will have to watch expenditures. We certainly will do that, Mr. Chairman, when these hearings are closed.

[The information follows:]

ALTERNATIVES AVAILABLE FOR THE FEDERAL GOVERNMENT TO STIMULATE INTEREST IN THE PRIVATE SECTOR USE OF COAL LOCOMOTIVES

From the Energy Department's perspective, the nation's modern railroad industry, which benefits considerably from the movement of coal, is a prime candidate for converting back to coal use in a cost-effective and environmentally sound manner. A key signpost of whether a technical concept is really valid is the willingness of industry to invest its own funds in a development effort. The recent initiatives within the rail industry such as the Norfolk Southern project with General Electric provide a positive indication of private sector interest. The Department's efforts to assist industry are focused on establishing a suitable technology data base in several related areas. The Fossil Energy program that is focused specifically on this program is the coal-fired heat engine program and particularly the diesel applications.

The diesel engine is one of the mainstays of our industrial sector with by far its major application being in the railroad industry. The diesel engine is efficient, very compact, easily assembled and shipped, reliable, cost-effective, and it does not require substantial lead time for design and fabrication. However, like many of the power systems that have been developed in this country during a period of cheap liquid fuels, it really has a major drawback and that is, it is wedded to the use of clean distillate fuel.

Given the uncertainties on energy prices and possible supplies, it becomes encumbent upon those heavy users of these premium fuels, like the railroad industry, to begin looking for new energy alternatives and to expand the range of acceptable fuels.

There are various technological approaches that could better prepare the industry for the potential of long-term supply uncertainties and price hikes.

One approach is to squeeze more useable energies out of our fuels that are available. This is being done through the development of higher-temperature diesels. In these engines, combustion takes place at several hundred degrees hotter than normal, promoting more rapid and complete combustion. Several private sector firms are pursuing this approach, and the Department of Defense is funding some work in this area.

The approach which the Department is most interested in is the development of alternative fuels, particularly those based on coal. Considerable amount of work is underway here in the U.S. and in Europe to develop diesels which are compatible with lower quality fuels such as residual oil and synthetic liquids. But in recent years, the Department, along with several private firms, has begun pursuing an alternative approach, the use of coal slurries, which is a mixture of coal and water predominantly although in some cases methanol is added to it.

The goal of that program is to produce a coal-based fuel that behaves much like oil. It flows like oil and has many of the same combustion characteristics and it can be burned cleanly.

If such a fuel becomes practical, the advantage for the rail industry is an economic fuel based on coal that can replace petroleum as a fuel for the propulsion hardware of the locomotive. For the coal industry, the rewards lie in the potential for restoring an old market using cleaner, more efficient modern-day technology.

Prospects for achieving a high quality, fine particulate slurry have been heightened by recent developments, particularly in fine grinding and coal cleaning. Research has shown the technical feasibility of producing micron-size coal, that is coal much finer than talcum powder, that has an ash content as low as 0.1 percent. Also, the use of advanced chemical and physical coal preparation techniques are being pursued, including the application of ultrasonic grinding and microwave cleaning, offer the potential for major steps forward in the technology of cleaning coal.

Also, parallel advances are being made in slurry research. The Department has an aggressive program that addresses the fuel form, its characteristics, and its performance in a wide variety of end uses. The private sector has also taken much of the initiative to explore coal-slurry preparation and applications concepts.

Research is also being conducted on the diesel engine itself and here efforts are two-pronged. First, under the Assistant Secretary for Conservation and Renewable Energy, coal slurry fuels are being evaluated in large, European designed and fabricated slow speed diesel engines. The principal application for these units is intended mainly for stationary industrial cogeneration.

The program overseen by the Assistant Secretary for Fossil Energy, on the other hand, is aimed towards U.S. medium speed engines -- that is, those engines that operate in a range from 300 to 900 RPM and are more widely used in the rail, the tugboat, the industrial and the utility sector. This activity is in its initial stages. Specifically, evaluations are being performed on the combustion of emission characteristics of premium quality and experimental slurry fuels under test conditions simulating those medium speed diesel applications. Also, examinations of the effect of these fuels on the engine parts -- for example, the injectors and cylinder liners in the conventional engine configuration and in advanced, ceramic-lined high temperature engines are underway.

In addition, there are other technologies sponsored in the area of the Fossil Energy R&D program that may be useful to the locomotive and transportation application. These include work in the gas turbine burning coal or coal-derived fuels and in fluidized bed combustion. The Department of Energy has recently undertaken a program to bring coal fuels to gas turbine engines. The technical problems are difficult, just as they are in coal-fired diesels. But the potential of using coal directly is a good incentive to pursue this technology. The major U.S. turbine manufacturers are each involved in the DOE program and the interest has continued to build for that technological area. Fluidized bed combustion of raw coal, even poor quality coal, is a near commercial technology especially in the size of interest to the locomotive use. The problem is in the packaging of the boiler in the size and shape for a practical locomotive. This technology has the potential to remove the impediments of returning the coal use to locomotives, which is the sulfur oxide and smoke emissions.

In summary, these are the areas where the government has an appropriate role in establishing a data base of generic information from which industries like G.E. and Norfolk and Southern can draw for use in their own development efforts. The emergence of this new array of technological concepts, coupled with uncertainties in the future prices and supplies of conventional liquid fuels, has led to a resurgence of interest in the coal-fired rail system. If a solid foundation of technological knowledge can be established, then industry will be properly positioned to take the next steps to apply that technology.

Senator **Warner**. Mr. Secretary, I am certain that you will and I wish to assure you that the Congress has taken note of these hearings and this potential and the Senate Coal Caucas will be receiving a report from me on these hearings very shortly. I just hope the Congress doesn't get our ahead of the Department of Energy. I urge you to look over the record together with your Secretary and others. I will be discussing very short term. Mr. Evered, would you care to comment on this?

Mr. **Evered**. Mr. Chairman, I couldn't add a thing to what's already been said.

Senator **Warner**. Mr. Evered, could you provide the subcommittee with the comparison of equivalent cost of coal as a fuel, for example when the rails abandoned coal in 1950, and what that cost comparison would be today.

Mr. **Evered**. Mr. Chairman, back in the late 1950's, diesel fuel was costing American railroads about 9.5 cents a gallon and coal a little over $6 a ton. These figures come from the Association of American Railroads. We at EIA cannot collect price information for fuels at that level of detail; that is, to railroads specifically. As recently as 1982, diesel fuel was about 95 cents a gallon, and coal well over $60 a ton. The price differential between diesel and coal on an energy equivalency basis, that is, the cost per million Btu's, has gone up tenfold, from 45 cents to about $4.40, in that period of time. Now clearly, anything the railroads could do to reduce their fuel costs, such as changing to coal or some other fuel, would be to their advantage and to the advantage of shippers.

Senator **Warner**. Secretary Merklein, could you advise the subcommittee on what efforts, in a general way, are being undertaken by other nations in the world to develop alternative transportation fuels. That is, alternatives to oil?

Dr. **Merklein**. Mr. Chairman, in Germany, for example, the preoccupation is with tests and development of methane, methanol, hydrogen, and the use of batteries. There are some 700 to 1,000 test cars running throughout Berlin using different types of fuels. The Department of Energy has a joint pilot plant scale research program with the German Government under which 100-barrels-a-day methanol is converted to gasoline. Methanol, of course can be made from coal. In the United Kingdom we have a country that is like the United States, blessed with immense coal deposits. So the emphasis is on the utilization of coal. Mostly of the effort, however, in the area of the more efficient and cleaner burning of coal. The U.S. Department of Energy helps in a joint research effort on pressurized fluid bed combustion. The United States, I might add, helps indirectly through the IEA, the International Energy Agency. Japan is looking at three different coal liquifaction processes. They also deal in other areas such as hydrogen production, storage and use. And I don't think it would be of interest to the railroads, but they do have under commission for Australia a coal fired seagoing vessel. New Zealand is very active in all kinds of resources including petroleum gases, compressed natural gas, and synthetic gasoline made from methanol. Many other countries are also active in the area. Australia, for example, is building a commercial size ground coal liquification plant. In Brazil, to some considerable extent, they also deal with methanol from sugar cane. In the

United States, demonstration projects concerning coal liquifaction, are usually done with the help of the Synfuels Corp. DOE is no longer involved in these kind of operations. We do research, we do contribute, for example, to the pressurized fluidized bed technology but have no fossil fuel demonstration plants.

Senator WARNER. But you do have the big facility here in West Virginia that I visited. They're performing a number of experiments in the area of research and development.

Dr. MERKLEIN. I have to defer to my colleague on research and development of that project.

Senator WARNER. I understand but, in summary, the other nations of the world are rapidly seeking altenative fuels to oil, principally coal, and in some cases looking to the application of technologies on their rail systems?

Dr. MERKLEIN. I would agree with you in every respect, except perhaps one. Its not exclusively coal. It is others. For example, in the nuclear area, the developing gap on imports is closed, to a considerable extent, by nuclear energy in many nations abroad. France and Switzerland produce almost 50 percent of their electricity from nuclear. And the clean burning of coal projects that we undertake may very well also be used in indirect ways for automobile, locomotive fuels through the conversion of the combustion energy to electricity and electrification of the rail system.

Mr. VAUGHAN. Mr. Chairman, the administration's approach to dealing with an oil shortage is primarily first to reduce the likelihood of such a shortage occurring. We think major efforts have been made and a lot accomplished in that area, and we have all mentioned this earlier in this hearing. And the fact that it primarily takes place in two areas: The reduction of imports *per se,* which have gone down considerably, as well as the diversified sources of supply. However, one does finally reach the point as Dr. Merklein has testified to a few minutes ago. But still, some 30 percent of our oil is imported and thus we do have significant vulnerability. What happens then if we are actually cut off from that oil is I think the thrust of your question. And there, as we know, the principal mechanism employed is the marketplace to distribute and allocate fuel. We've found in the past decade the attempts of the government to perform this function were counterproductive and made the situation even worse. In addition, there is the Strategic Petroleum Reserve which is a major accomplishment of the administration, where we have stockpiled vast quantities of crude oil to be introduced as we find substantive in the event we're cut off. I am happy to report that program has, during this administration, passed its halfway point. And previous to this administration very little had been accomplished other than the Congress passing a statute and then trying to get the various administrations to actually implement it. And as you well know, under the broad committee leadership and under the subcommittee that you head, sir, you have helped see to it that we have rigorously approached the filling of the reserve. Finally, we attempt to mitigate the economic harm that might occur as prices rise through economic process. Let me mention, however, some specifics that may be of help to railroads, whom as you have pointed out are considerably reliant, at this point, on oil or diesel fuel. We have done a great deal to encourage stockpiles, primarily, by two mechanisms. We have removed price and allocation controls which robbed those who planned the stockpiles of the fruits of their labors. That has been totally withdrawn. And we have made it possible in this administration that fuels in our stockpile for use by the private sector will not be seized by Government or employed for some other purposes. And we have also assisted associations and groups of consumers in actually arranging for stockpiles, as have been requested. We also have drafted and have ready to implement if necessary the forms of requests and procedures which would be employed for reducing things like Clean Air Act restrictions that restrict the use of fuels like coal so that the Nation can quickly shift in the short term over to more reliance on coal. And we have encouraged to the maximum degree possible multi-firing installations in things like powerplants, industrial powerplants, and in industrial boiler houses so that a variety of fuels can be used. And there again the fuel most likely to be used in a shortage of oil would be highlighted by coal, since this fuel is so abundant. I think that covers the list of specific things in which you would be interested.

Senator WARNER. Thank you, Mr. Secretary. Mr. Evered, it is my understanding that a study was performed under your guidance relating to the impact of coal on railroad deregulation. The study reached the conclusion that railroad deregulation will increase the delivered cost of American coal and thus affect American coal competitiveness in the domestic and international markets. Now, if we were to return to the use of coal in some percentage as a fuel for railroad locomotives, would that not lower the cost of goods transported by rail?

Mr. EVERED. Yes, Mr. Chairman, it very well could. Simply switching from diesel fuel to coal could achieve as much as 64-percent savings in fuel cost, which translates to about 18-percent total transportation cost. That assumes that there would be no increase in the fixed cost of moving to the coal-fired equipment as you replace the locomotive stock with coal fired locomotives. That assumes that those are the same costs.

Senator WARNER. Let's clarify that as that's an important part of the equation. As the rail system were to retire an existing locomotive which has fulfilled its use or life, technically, then it would add to the system a new locomotive of comparable cost but fueled by coal. I think that's your premise?

Mr. EVERED. I don't mean to imply that I'm saying a coal-fired piece of equipment would cost the same as oil-fired. I don't know.

Senator WARNER. Well, we have to use some assumptions in order to make an analysis.

Senator EVERED. Using that assumption, there would be an 18-percent total transportation cost saving using coal. Now, since transportation averages about 24 percent oof the delivered cost of coal being shipped, that could translate into better than a 4-percent savings to the consumer. And given our estimate of what the price of coal to industry will be in the year 1990, that could mean $2- to $3-a-ton savings, which certainly could be significant.

Senator WARNER. One of the main objectives of this Nation trying to recapture some of the lost international markets in coal is to reduce the price of coal. I've been meeting regularly with all parties the rails, the coal producing people, the unions both rail and coal—and I'm hopeful that at some point we can perhaps reach a voluntary consensus on this issue. An agreement can be reached by all interested parties to make what adjustments are necessary in cost, rates, other factors to lower the cost of our coal and to try and recapture this international coal market. Its a good one for the United States, particularly since we are such a major producer of coal.

If we could in the foreseeable future lower transportation costs, it would give us a competitive edge in that world market.

We're here today perhaps at the threshold of this new technology. It will be many years before it can be transformed into a meaningful part of the equation in reducing costs, but if somebody doesn't make a start here today, tomorrow of the next day we're going to be lost in this international market in my opinion. I don't want to see our wages paid for coal production driven down or even have in any way an attempt made to drive them down to compete with the South African wage. Accordingly, we've got to turn to new technology to lower our cost of our coal and give us that competitive edge in the world coal market.

Mr. **Evered**. Mr. Chairman, as you and I have discussed in the past, the United States is a very large supplier of coal for the world market. We are, unfortunately, at present a high cost supplier. So it is critical to lower the delivered price of coal to our international customers and thus improve our market share.

Senator **Warner**. We have covered a good deal of ground here today. you have given the chair a number of points here.

Mr. Secretary Harrington, understanding, of course, that the President's budget will not be released until the end of the month, can you give us any insights about what to expect in fossil fuel research and development compared with the fiscal year 1984 budget?

Mr. **Harrington**. Sir, I really have no data with me that I can use to answer that question. Perhaps I can approach it this way. The Department of Energy has a level of effort underway in the research and development area. Most of these activities are multiyear activities and to may knowledge we're not expecting a major perturbation in the local effort, that we will be engaged in as we transit from 1983–85 fiscal years. I prefer, if I may, to give you a more detailed answer on that.

Senator **Warner**. Yes, of course. We'll have the appropriate hearing in my committee, the Energy Committee, on the budget and I hope we can expect to learn from the President, the Secretary of Energy, that this Nation is moving ahead with increased funding in the area of research and development, seeking alternative fuels.

Mr. Evered, returning again to some of the valuable work that you and your colleagues have done, I understand in your recent short-term energy outlook you forecast a 26-percent increase in oil imports. Over what period did that take place and what were the factors which led you to that conclusion?

Mr. **Evered**. Mr. Chairman, that compares the total imports for the year 1983 to what we project for this year, for 1984. It is fairly straightforward. It implies an increase in demand for petroleum in the United States as industry recovers, if economic growth continues to take place, to the tune of about 800,000 barrels a day of increased oil requirements. In addition, we expect to see a modest increase in the amount of inventory build-up. Inventories were drawn during 1983; we expect to see——

Senator **Warner**. Drawn down?

Mr. **Evered**. Yes, drawn down. We expect to see a lot of build in that which would increase the need for oil. At the same time, domestic production of crude will decline very slightly, we expect.

Senator **Warner**. Permit me to rephrase what you have said. As this country enters this period of economic recovery—I think there are strong indicators to that effect—the Nation really has no alternative but to look to oil to help fuel that recovery. In the short term?

Mr. **Evered**. In the short term, that's correct. Plus natural gas, and, naturally, industry will choose the source most econmical to them.

Senator **Warner**. Well, unfortunately the Congress has not unraveled the natural gas problem. We all have been involved in that during the last session of Congress and maybe we'll tackle it again. I just wish to emphasize, by virtue of your testimony on this point, the need to explore alternative sources of energy, particularly coal, in this Nation. When we have the blessing of an economic recovery period, we simply have to go beyond the shores of the United States to look for the short-term energy sources and use that for demand in recovery?

Mr. **Evered**. That is correct.

Senator **Warner**. So again I come back to the point that hopefully we can devise an engine for the rail system which will allow us in future years of economic recovery to not have to go abroad for energy.

Dr. Merklein, I'm hopeful that as the United States proceeds with the efforts to develop coal-burning locomotives, you and others of the International Energy Agency will keep our Allies advised of the progress we are making. Eventually this technology may be exported from the United States. Indeed, the United States is currently one of the major exporters of locomotives, I have learned, in the world. The making of these locomotives creates jobs within the United States. So if we were to devise a technologically feasible coal-burning engine, that could come a valuable part of be our export market. Am I not correct?

Dr. **Merlein**. Our emphasis has been to respond to environmental concerns associated with coal, and to go after the area of clean burning of coal rather than the direct coal burning locomotive. In this effort we have participated bilaterally and through the IEA, on varied fronts as I have indicated. Given that research effort, I believe that break-throughs will be inevitable. And when the day comes that coal is viewed as an environmentally clean fuel, I am sure that the application in locomotives will not be lost on industry and will not be lost by the various participating governments abroad.

Senator **Warner**. Well, I wish to assure all who have followed the proceedings of this subcommittee that the record in the previous two hearings contains numerous references to the question of the environment. The record carefully documents the opinions of both technical witnesses to the effect that the state-of-the-art now of burning coal is such that, a coal-burning locomotive or a locomotive utilizing coal for fuel will have an environmental impact below that of existing diesel engines on the rail system. From the testimony it is evident that we are returning to the old romantic steam engine which spewed sparks and noise and rattled down the rails. We are turning to an engine which is cleaner than the existing diesel locomotive today. Therefore this whole effort would move us forward in the area of the environment is a positive effort. I believe that concludes the questions. I have to the panel of representations from the Department of Energy. I wish to collectively and individually thank you and your Secretary for allowing you to come to Virginia today to share your very valuable contributions on this question. Thank you very much for coming.

STATEMENT OF HON. JOHN H. RILEY, ADMINISTRATOR, FEDERAL RAILROAD ADMINISTRATION, DEPARTMENT OF TRANSPORTATION, ACCOMPANIED BY ROBERT McCOWAN

Mr. RILEY. The bottom line is that in our view, conversion from diesel fuel to coal would mean an operating saving of anything from about 40 percent up to 55 percent for the Nation's rail carriers. Now we are in an era where, for the first time in history, the cost of fuel actually exceeds the cost of labor to the rail industry. When you measure the potential savings of coal against the drain that fuel costs are having on the industry now, I think it defines the kind of incentives that we believe, at the FRA, will lead to the creation of prototypes within the next 5-year period and the actual operation of some prototype within the decade. And I think, Senator, that your assessment and the committee's assessment of what the private sector is doing and where its going is very accurate. I've gotten a little ahead of myself in saying that but I did want to jump into the question that was asked of the last panel. At least I think, in dealing with the railroads every day and understanding their attitudes, I have a slightly different view of that than the last panel.

Senator WARNER. What are the various options that would be equitable from the standpoint of the American taxpayer to develop these new prototype engines? What options are equitable to consider being offered to the private sector as an inducement to proceed with the necessary research and development?

Mr. RILEY. Senator, let me say at the outset that the ability to take a component of your operating cost that exceeds 10 percent and cut it in half is an extremely powerful incentive to invest. In the last year, you've seen three of the Nation's major rail companies, Norfolk Southern, CSX, and the Burlington Northern, respond to that incentive by making investments.

Senator WARNER. In this technology?

Mr. RILEY. Yes, in this technology. In fact, Senator, I was speaking with some senior officials at CSX last night and I mentioned that I was going to be here this morning and they said to be sure to tell the Senator that the commitment we've made to research and development in this technology is just the beginning, in our view, we are going to go further.

Senator Warner. The subcommittee will be hearing from CSX formally today. One of its witnesses, Mr. Kenneth Morris, is recognized as perhaps leading this technology.

Mr. Riley. It's my judgment, Senator, that the cost advantages are a powerful incentive to invest. I think that through changes in the tax law that were made by this administration—and we supported it 2 years ago and magnified that incentive—the liquidity has come to the railroads in the course of the deregulated environment that has magnified their capacity to respond to that. And while I haven't thought about this in a great deal of detail, I think the committee is on the right track if it looks at the tax and investment incentive programs that have worked so well in the whole area. We are happy to work with the committee on that.

Senator Warner. Well, I'm inclined, at this time, in a very preliminary way, to consider those as the principal options by which Congress can provide the legislative framework for that incentive to be conveyed to industry. At this time, direct grants seem to me to have less appeal.

Mr. Riley. They also involve us in choices of technology.

Senator Warner. That we don't want to be involved in. It's my judgment that the Federal Government should provide industry with full knowledge of the subject. The decision as to the type of technology within the framework and goals has got to be done in the private sector.

Mr. Riley. I agree very strongly with that, Senator, I don't believe we would be doing the industry or the cause of coal development a favor by having my agency, even under my administration, making those kinds of decisions. They are outside our purviews. And also, at a time when research dollars are so scarce, to place-rank dollars into an area where there is so much private investment would be a disservice to other priorities in Government.

Senator Warner. Please continue as you had planned and then I'll have several questions.

Mr. Riley. It is, believe me, my pleasure and not a chore to come down from Washington this morning. It isn't very often that you can talk about the past and the future of any industry in exactly the same words. The coal-powered locomotive provides us with that opportunity and it is my pleasure to be able to share my views and the views of the Federal Railroad Administration with so many. To put those views as succinctly as I can, we believe that coal-powered technologies can plan nearly as great a role in the future of the rail industry as they have played in the past. There have always been advantages unique to coal as a locomotive fuel. Notwithstanding those advantages, the old coal locomotives were driven from the rail lines because we lacked the technology to refine the advantages and adapt them to the particular needs of the rail industry. Technology has come a long way in the last 30 years and we believe it's now an appropriate time for the industry to look forward to the future by looking back into its own past and make the kinds of investments which we've begun to make in coal development. It's a fun issue to deal with, as I'm sure the committee has discovered, because it blends elements of space age technology with historic romance. I think America has been entranced by the romance of the coal powered engine since the first steamer cut its swath across the wilderness and began drawing the map of Virginia and of this country.

Senator WARNER. What was the word you used, with reference to the map? You said it began to what?

Mr. RILEY. It began to cut a swath across.

Senator WARNER. And something else?

Mr. RILEY. And began to draw the map of Virginia and of this country. Well, I don't say that I can speak it as well as others. A lot of railroad men are poets who've tried to capture that concept without a great deal of success. I think the one who did it the best was a man named Graham Claytor, the former president of the Southern, and a former Secretary of the Navy.

Senator WARNER. I know him well.

Mr. RILEY. And I would be remiss if I did not read a brief statement about coal power into the record. Clayton said——

Senator WARNER. In what capacity did he make this statement?

Mr. RILEY. This was in his former capacity as president of the Southern, when he bacame well known for trading two new diesels for two steam engines. He was looking farther ahead than most people realized at the time, I think. But he said:

> The wedding of steam and steel was one of those rare combinations of beatuty and utility that have a timeless appeal to the imagination. Steam locomotives were more than machines, they were destiny on wheels. Their power was awesome and their prize, the Nation was linked together with steel rails. White plumes of engine smoke streamed above the land like the banners of the conquering host.

Senator, it was economics and not romance that made the steam engine the predominant form of transportation for so many decades. And, in the end, it was economics that drove it from the rail. America's railroads, in the late 1940's, were operating some of the biggest, fastest steam engines found anywhere in the world. But speed and size weren't the only attributes needed by the rail industry. The old steamers needed to be rewatered every 50 miles, more or less, depending on the technology. That slowed freight—and that was a very expensive proposition in the West where water was scarce. They required an enormous amount of maintenance and suffered a tremendous amount of down time. The great weight of the old steam engines took a tremendous toll on the track and the roadbeds. They were inefficient energy consumers and steam locomotives of that era lacked the operating flexibility to operate over the different terrains that railroads have to operate over to be true national systems. This factor, as much as any other factor, led to the demise of steam. In the late 1930's and early 1940's, American industry began to market an excellent competitor to the steamer, the early diesel locomotive. And that touched off the most historic change in the history of our industry to this day, which was the dieselization of the fleet. In the early 1950's, as many as 3,000 diesels a year were brought online, which was 10 times the replacement rate of the previous year. Steam's market share went from 80 percent to 35 percent in just 10 years. And by the end of the 1950's, steam was completely gone from the main lines of this country.

Now it's ironic, Senator, that the same economics that drove the coal-powered engine from the Nation's rail lines has now gone full circle and they're about to bring it back. Fuel costs in the 1940's, were about 5 or 6 percent of railroad operating revenues. They'd risen to 7 percent by the early 1970's and with the doubling of petroleum costs in the 1970's, they are now at 12 percent. And, as I indicated, that now for the first time exceeds labor costs in the industry's operating cost revenues make-up. The changing economics of energy are driving railroads back to coal. The key factor is that technology has now advanced to the point where coal is a viable option for railroad locomotion. In the late 1970's, the Federal Rail Administration playing a small role in the development of those technologies by cooperating with the Department of Energy in initiating a research project on the use of alternate fuels, including coal-based fuels, in existing locomotives. While we are no longer involved in that venture, it's been picked up by the Association of American Railroads, many suppliers and a number of the Nation's largest rails. As I've mentioned, three of the Nation's biggest railroads have already made investments and I believe you will see more. They've invested in a variety of technologies. Turbines, reciprocating engines, the use of coal in conventional internal combustion engines. The bottom line to it all, Senator, I think is that the advantages of using coal as a locomotive fuel have always been apparent. We have now caught up technologically in several ways to the point where it's feasible to use it. We now can utilize microprocessors to control the function of the whole engine and provide it with the operating flexibility that it lacked back in the days of the old steamer. We have boosted thermal efficiency enormously. Back in the 1950's, it used to take about 3.5 pounds of coal and 22 pounds of water to produce 1 horsepower for 1 hour. Today it's about 1.5 pounds of coal and 9.5 pounds of water and I think we can improve on that with research. You're talking about a two-maybe a threefold increase in efficiency of operation, but we have technologies today that we didn't have 30 years ago. We have devised a means to limit the environmental impact by controlling noise and ash disposal. We have pioneered lightweight metal to produce engines with the same power that are far far lighter and have less impact on the Nation's rail system.

Finally, and this is so critical, the new technologies involve closed cycles for water. The prototype designs of today's coal-based locomotive can go about 500 miles without refueling and up to 1,000 miles without rewatering. And that makes them comparable to diesels in most operating environments.

Now, Senator, I don't want to say that it is entirely upside. There are obstacles to be overcome. The primary obstacles, I think, are three. One is the fact that there is an infrastructural cost for transition into any kind of different system, particularly if it's a dual diesel coal system. You need to build the coaling facilities. You need to train your work force. You need to maintain dual inventories. That's the first problem. The second is environmental. Environmental in the sense that no one really knows what they're dealing with. We did not have environmental standards in the days when the steam engine roamed the tracks of America. So as the railroads work to devise today's steamers, they don't know the environmental standards they are going to have to deal with and that's an issue. The third issue is train track dynamics. In the days of the old steam engine, we used to have 39-foot jointed rails that had a lot of flex, so as the steam engine moved down the track with the pounding, there was some flex in the rail. Today the system uses predominantly continuous welded rail. We really don't know what the impact of a modern steam engine on continuous welded rail will be. These are all issues, Senator, but I think they are all surmountable issues. We are dealing with many many issues in the Federal Rail Administration where the end-line gain is nowhere near as great and the obstacles to overcome are much greater. It's my view that the coal industry and the railroads working together will resolve these problems and bring coal back as a locomotive fuel. It's fitting that that happens because the rail industry and the coal industry have been mutually dependent for decades. Most of today's railroads—many of them at least, if not most—were created and built to bring coal out of the coalfields. For many years, they were coal's greatest consumer. Coal is now the major item that the railroads transport. It's only fitting that they should tie their futures together as they have been tied in the past.

Thank you, Senator, I thank you very much for the opportunity to be here.

[The prepared statement of Mr. Riley follows:]

TESTIMONY OF JOHN H. RILEY
ADMINISTRATOR OF THE FEDERAL RAILROAD ADMINISTRATION
BEFORE THE SUBCOMMITTEE ON ENERGY
AND MINERAL RESOURCES
OF THE SENATE COMMITTEE ON ENERGY AND NATURAL RESOURCES
JANUARY 19, 1984

Mr. Chairman. It isn't very often that we can talk about the past and the future in the same words. Coal-powered locomotives provide that kind of opportunity, and it is a privilege to come before this Committee to share my own views and the views of the Federal Railroad Administration on the future of coal as a locomotive fuel.

To put those views in the simplest possible terms, we believe that the future of the railroad industry will be tied almost as closely to coal power as its past. There are unique aspects to coal that diesel fuel cannot duplicate. The steam engine gradually lost its dominance in the railroad industry because we lacked the technology to refine and harness those advantages. Technology has evolved over the past thirty years, and this is an appropriate time for the American railroad industry to look forward to its past by reinvesting in coal power.

America has been entranced by the romance of steam since the first steam engine cut a swath across the wilderness to draw the map of this country. A lot of people--from poets to railroadmen--have struggled to define that appeal. But I don't think anyone has come closer than Graham Claytor, former President of the

Southern Railway, former Secretary of the Navy, and the present Amtrak Chief Executive Officer, when he said:

> ". . . The wedding of steam and steel was one of those rare combinations of beauty and utility that have a timeless appeal to the imagination. Steam locomotives were more than machines--they were destiny on wheels. Their power was awesome and their prize a nation linked together with steel rails. White plumes of engine smoke streamed above the land like the banners of a conquering host."

It was economics, not romance, that made the coal-burning locomotive our preeminent transportation vehicle. And it was economics that lead to the demise of the steam engine in the late 1940's and early 1950's.

In that era, the U.S. railroads were operating some of the largest, fastest steam locomotives in the world. But weight and speed were not the attributes the railroads were seeking in freight locomotives. Their operations were concentrated more and more on long freight trains operated at relatively slow speed over long distances and varied, often mountainous terrain. At that time, the attractions of steam were more than countered by its inefficiencies:

- The traditional steam locomotives had to be rewatered as often as every 50 miles. In areas like the Southwest, where water was scarce, the added costs were enormous.

- They had to be taken off the train and serviced as often as every 100 miles, and they required full inspection and maintenance checks at monthly intervals to ensure safe operations. This meant considerable down time and reduced utilization of the locomotive, and made rail service less time-competitive.

- The heavy engines with their rhythmically stroking pistons took an enormous toll in track maintenance.

- The old steam engines were inefficient energy consumers, because we lacked the technology to transform a high percentage of the heat content of the coal into useful power.

- And the steam locomotives of the earlier era were not sufficiently flexible to permit efficient operations over the varying terrains and conditions they faced.

After the decade of the 1930's and the World War II years when railroad investment in new capital plant dropped to historically low levels, the railroads needed new locomotives. At the same time, American manufacturers were marketing a new, highly practical diesel locomotive for freight service, offering clear advantages over the majority of the steam locomotives in the fleet in efficiency, flexibility, and maintenance cost.

The ready availability of cheap and reliable supplies of diesel fuel and the interest of the railroads in pursuing a clean, modern, efficient technology combined to create the most dramatic change in the history of our railroad industry--the dieselization of the locomotive fleet. From an average of only 340 new locomotives installed by the railroads each year between 1932 and 1943, in the next five years an average of 1,300 per year were installed, and between 1949 and 1953 the figure rose to nearly 3,000 per year. Between 1944 and 1953, nearly 30,000 steam locomotives were retired. Steam locomotives' share of freight traffic dropped from 80 percent to 35 percent in only 10 years, and by the end of the 1950's steam locomotives had disappeared from mainline freight service.

The coal-carrying railroads were the last to abandon steam. Some of the railroads would have kept their nearly new steam locomotives in service even longer if it hadn't been for the increasing cost of repairs and the lack of spare parts. The Chesapeake & Ohio and the Norfolk & Western pursued research on coal-burning turbine engines through the 1950's in an effort to find a way to continue to use the ready reserves of coal so convenient to their service area. But the high capital cost and maintenance problems they encountered offset any savings they could foresee on fuel expense, and even the coal-carrying railroads resigned themselves to the supremacy of diesel fuel.

In the early 1960's some railroads continued to investigate prospects for gas turbines and substitutes for high-grade diesel fuel, but after that point research on alternatives to the diesel was largely abandoned.

In the 1960's and 1970's, fuel took up less than 4 percent of the railroads' total operating revenues. However, between 1973 and 1974, that figure jumped to 7 percent, as diesel fuel prices doubled. The cost of diesel fuel doubled again between 1978 and 1980, bringing the fuel ratio up to 12 percent. Despite a nearly 30 percent improvement over the past 5 years in the ton-miles achieved per gallon of fuel consumed, the railroads still spend more than $3 billion a year on fuel, and they are justifiably concerned with finding means to achieve further savings in this significant sector of expenses, and avoid the fuel price shocks and threats to supply they experienced in the last decade.

It is ironic, Mr. Chairman, that the economics that drove the coal-burning locomotives off the American railroads have now run full circle and are about to bring it back. Rapid advances in technology have made that return conceivable.

In the 1970's, the Federal Railroad Administration played a key role in that process, initiating a project in cooperation with the U.S. Department of Energy, to investigate the prospects for using alternate fuels including slurried coal or other coal-derived substitutes in existing railroad locomotives. The Association of American Railroads (AAR), locomotive suppliers and individual railroads have picked up and expanded on that research in succeeding years. Other groups are developing designs for entirely new coal-powered locomotives, including turbines, reciprocating engines updating traditional steam locomotive designs, and coal-based variations on internal combustion engines. Norfolk Southern, CSX, and Burlington Northern Railroad have each contributed to research on coal-burning locomotives being undertaken by companies such as General Electric and American Coal Enterprises.

The advantages of using coal have always been apparent. What is making the difference today is the development of technologies that can adapt those advantages to the needs of the nation's rail system. We are now better able to:

- improve thermal efficiency of coal-burning locomotives
- limit environmental impacts by controlling smoke, noise, and ash
- build up strength and reliability without adding weight to the locomotive, through use of new, lighter metals
- utilize microprocessors to provide operational flexibility the last generation of steam locomotives did not possess

Commitment of private research dollars to the development of coal-powered engines is increasing. In the role of banker of ideas for the railroad industry, the FRA will continue to encourage the private sector in its efforts to find low-cost, efficient fuel alternatives, including coal. Of course, one of FRA's primary roles is also to ensure the safety of rail transportation and as new technology develops for railroad use of coal, we will also be monitoring the safety implications. Individual railroads will be evaluating the initial purchase price of locomotives, relative fuel costs and other operating expenses, maintenance needs, and overall operating characteristics. I believe the changing economics of energy will drive the railroads back to coal and we will see the large-scale return of coal-burning locomotives to American railroads within the next decade.

Of course, this is not to say that the railroads can or will undertake an overnight replacement of their present locomotive fleet. Of the nearly 28,000 locomotives now in operation on our freight railroads, approximately 45 percent were built in the years since 1970. The substantial service life remaining in the present diesel fleet, the efficiency of the existing units, and the considerable capital required to build plants to produce new locomotives and to install them in service mandate a gradual replacement.

The relationship between the railroad industry and the coal industry has always been one of mutual dependence.

- Many of our railroads were built to open up the nation's coal fields.
- For years, railroads were the major consumers of coal.
- Railroads are now the major carriers of coal.

I am confident that we will see the railroad industry and the coal industry together find an economical way to bring coal back into the range of railroad fuels, and that the two industries will share the mutual benefits of increasing consumption of this rich indigenous fuel.

U.S. Department of
Transportation

News:

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NEW-TECH IRON HORSE MAY STAGE COMEBACK ON RAILROADS, RILEY SAYS

The coal-powered steam engine, which chugged across the country in the heydey of the railroads, may be making a comeback, according to John Riley, Administrator of the Federal Railroad Administration.

However, the new version would have lower energy costs than the current diesel-powered locomotives, Riley said in testimony before a Senate Energy and Natural Resources Subcommittee hearing in Richmond, Va.

Riley said, "The changing economics of energy are driving the railroads back to coal, and rapid advances in technology have made that return possible." Sen. John Warner of Virginia chaired the hearing of the Subcommittee on Energy and Mineral Resources.

As energy prices have risen, the cost of fuel for diesel locomotives has become a major part of railroad operating budgets. The prospect of a new-technology coal-powered steam engine with lower energy costs has prompted several private sector companies to sponsor research in this area. After World War II, the railroads phased out steam engines in favor of diesel locomotives.

New technology is being developed that would reduce noise and emissions, recirculate steam into water, and achieve more operational flexibility through the use of computers, Riley noted. Recirculating steam into water would avoid the need for engines to stop for water.

"The old steam locomotives were heavy and slow, and took an enormous toll on the tracks," Riley said. "They needed a lot of maintenance and inspections, along with frequent stops for water--a difficulty in regions which were short on water.

"The new technologies involve closed cycles for water and lighter stronger metals to alleviate the heavy wear on the tracks.

"Commitment of private research dollars to the development of coal-powered engines is increasing, and I believe we will see the large-scale return of the coal-fired locomotive to American railroads within the next decade."

Senator WARNER. I am grateful to you, Mr. Administrator for providing some of the most insightful, encouraging testimony that we've had in the record thus far.

Mr. RILEY. I appreciate that, Senator.

Senator WARNER. And it will be stated in its full form. Is there anything your colleague might wish to add?

Mr. McCOWN. At this point, I have nothing to add.

Senator WARNER. As I understand, you do the technical analysis and you have kept abreast of the various advancements in the technology?

Mr. McCOWN. Right. I have.

Senator WARNER. Do you have any question about the technical feasibility of an engine being brought on line if we really put ourselves down to a serious effort within a space of 5 years? A prototype?

Mr. McCOWN. I believe the prototype is possible in 5 years. The challenges are great. We have a lot of internal problems to solve.

Senator WARNER. Mr. Administrator, you've brought up a point that no one has mentioned heretofore in the hearings. You indicated we have to recognize that if the prototype comes into being it's going to operate on the existing system of rails. I hadn't thought about that before. I know just a little bit about railroading only because I have had a fascination with railroading throughout my entire life. What are the contingencies in that issue?

Mr. RILEY. Well, there are two issues, really, that we've identified so far. One is the one I mentioned. We have gone in the last decade largely from the old jointed rail, which was more flexible but far less efficient, to continuous welded rail. However, the new steam engines will not be as heavy as their predecessors.

Senator WARNER. Yes; I think the weight would be comparable to the existing diesel.

Mr. RILEY. That's correct.

Senator WARNER. In a very general way, the prototype that has been described to the subcommittee is one which, when viewed, would not be dissimilar to the profile or the weight of the existing diesel. Hopefully, it has been documented that it will be environmentally sounder. And, of course, more cost efficient. But no one has talked about its operation in terms of having a different impact on the rails.

Mr. RILEY. They do. The operating characteristics of the steam engine in the new technology has a much greater downward force. The best way I can describe it is to say there's a pounding. That's not to say that the tracks aren't perfectly capable of sustaining that. It is simply to say that we have no practical experience in judging it. Since it will fall within the purview of my agency, at some point, as we get closer to bringing prototypes out on the rails, we're going to have to analyze that issue. Currently, railroads operate old steam engines on a variety of runs. The Southern and some of the Chessie's are run over the continuous welded rail on single trips and they haven't derailed any, to the best of my knowledge. But that still doesn't tell us what repeated exposure will do.

Another issue is that there have been some slight adjustments in the gauge of the tracks since the steam engine went out. The AAR track standards moved the gauge a little bit closer together. That's the kind of problem I think one can compensate for in the design of the engine. But what it illustrates, I think, is that there's an enormous need for the various private sector companies developing these engines and the governmental agencies that will have to judge and regulate to work together from the beginning so that these types of issues can be taken into account. Now, I would like to see my agency sponsor a symposium in the course of the next year on the general subject of coal power and its potential for the future so we can bring the parties together. By bringing some of the skeptics in with the believers and talking about what problems are likely to be encountered, we make certain that such concerns are addressed simultaneously and that we don't lose time because an element of the equation has been left out at the beginning. We are also hoping to—and I think that we're close to finalizing this—host this major event with the Pan American Railroad System. It takes place every 3 years. It will involve participation of 45 to 50 nations in the United States this fall. And it would seem to me to be an appropriate topic to consider within the context of that congress. That, I think, is the biggest contribution that we can make at the moment, but I don't think it's an insignificant one.

Senator WARNER. Recognizing that the United States is a major exporter of locomotives, if we were to successfully develop this technology, even though it might not be adopted wholeheartedly by the U.S. rail system, is there not an export potential?

Mr. RILEY. There is a very great export potential. I think you are quite right to raise the issue of the supply industry. Our supply industry is about as close to being flat on its back as an industry can possibly be. We are a major exporter of locomotives but if you take what we are doing now and compare it to the markets that are out there, you realize that our penetration is very thin.

Every nation's railroad has its own operating characteristics. Rail systems tend to be unique—sometimes in their gauges, certainly in their signaling systems. Some are electrified. They adapt to energy resources around the world. What we've got to move toward is the ability to design the railroad equivalent of the world car. Something that has components that can adapt in a uniform way to all rail systems and then has other aspects that can be adapted from nation to nation.

The development of this technology makes a great deal of sense, particularly when you're talking with Third World countries that have enormous problems in gaining access to and affording imported oil. You have taken the first step toward addressing the real reason why we have not been able to penetrate those countries more effectively. I think there is great potential there.

Also, this factor raises another interesting point. There is no element in this equation that has more of an incentive to pursue research and development of this type of technology than the American railroad supply industry. They really need something that is a revolutionary breakthrough that will lead the rail industry to the earliest economically feasible phaseout of existing equipment. This type of technology could do that.

Senator WARNER. We thank you, Mr. Administrator, for joining us today. Have you got a program on now to fund alternative locomotive fuels?

Mr. **Riley**. We started the program but it doesn't exist today. We started the program in the 1970's. The AAR took the program over from us and they are now running it in cooperation with the Department of Energy. Of course, we work closely with them.

Senator **Warner**. So in that context your administration is looking at the substitution of coal for diesel fuel?

Mr. **Riley**. That's right.

Senator **Warner**. We're going to receive testimony today from the Department of Defense. Does your agency have any participation in any of the national planning in the event of a major defense contingency and the allocation of energy resources?

Mr. **Riley**. Yes, we do, Senator, we work closely with the Department of Defense on that and I think that is also one of the most powerful reasons for——

Senator **Warner**. Would you outline that subject as you understand it?

Mr. **Riley**. Let me be very general. We work with the Department of Defense to make sure that the capacity of the industry we regulate meets the needs of the Department of Defense. They define needs. We regulate the capacity to serve the needs. Obviously, the primary concerns with the rail industry are that we would have to move heavy military equipment for any conflict and have the access to fuel resources. We are virtually and completely a petroleum dependent industry, and frankly it does concern me that in the event we had to face a major mobilization, the military would have first call on the petroleum resources and that would greatly strain the access of the rail industry. That's not to say we couldn't exsist in that type of environment. But if we had the capacity to share some of that load with coal-fired technologies, we'd be in a more secure position. It depends—there is a lot more to say about that. In fact, I didn't cover that in my statement.

Senator **Warner**. The subcommittee will now turn to Major General Small, commander, Military Traffic Management Command.

Mr. **Riley**. Thank you very much, sir.

STATEMENT OF MAJ. GEN. HAROLD I. SMALL, COMMANDER, MILITARY TRAFFIC MANAGEMENT COMMAND, DEPARTMENT OF DEFENSE, WASHINGTON, DC, ACCOMPANIED BY ALLEN DOWD, SPECIAL ASSISTANT FOR TRANSPORTATION AND ENGINEERING, DEPARTMENT OF DEFENSE, AND MAURICE E. LePERA, CHIEF OF FUELS AND LUBRICANTS, FORT BELVOIR'S RESEARCH AND DEVELOPMENT CENTER

Major General **Small**. Good morning, sir. We have been designated to respond to your request to Secretary Weinberger for testimony on the importance of the Nation's railroads to national defense. I am accompanied this morning by Mr. Allen Dowd, my senior transportation engineer and Mr. Maurice LePera who is the chief of fuels and lubricants division at Fort Belvoir's Research and Development Center. We have prepared a three part statement which has been submitted for the record. First, we have presented some detail on the purpose, scope and accomplishments of the Railroads for National Defense Program. Second, as requested, we have included procedures which we have developed with the Departments of Transportation and Energy for priority allocation of diesel fuel for railroads engaged in support of national defense, as authorized under the Defense Production Act. And third, we have addressed the authority for funding the development of coal burning locomotives as requested. The Department of Defense relies upon the railroads to meet its peacetime, contingency, and mobilization requirements. Large volumes of defense equipment, ammunition and material are moved by rail. Particularly noteworthly is the reliance upon the railroad for the movement of oversized and overweight equipment such as battle tanks, tank retrievers, howitzers, bulldozers, and ballistic missile components. The lack of a viable civilian railroad capability could adversely impact defense installations and activities requiring rail service for completion of their assigned mission. In brief, the Nation's railroads comprise an essential link in the logistics chain needed to support any major defense contingency such as the reinforcement of Europe.

Because of military importance of the rail industry, we initiated a Department of Defense Railroads for National Defense Program. This program is designed to assure consideration of national defense requirements in plans, standards, and programs for the Nation's railway network. The Railroads for National Defense Program is closely coordinated with the Federal Railroad Administration of the U.S. Department of Transportation and with State and industry rail planners. Because of a threat of nonavailability of fuels for the common carrier industry during a defense contigency, we have developed with the Departments of Transportation and Energy procedures for emergency priorities and allocations of fuel for common carriers supporting national defense, as authorized under the Defense Production Act. With regards to the development of coal burning locomotives such motive power to exploit the use of domestic fuels and reduce dependence on foreign sources would have an obvious national defense benefit.

Senator WARNER. That is your key sentence.

Major General SMALL. Yes, sir. It could minimize the need for invoking priorities and allocations procedures to carry out the defense mission which could deprive the civil sector of a critical fuel source. While the Defense Production Act might be considered an authority also for the development of coal burning locomotives, we believe that any locomotive development efforts belong within the purview of the Department of Energy as the issue is not defense peculiar, but is commerce oriented and should be funded from civil sources. Mr. Chairman, we appreciate the opportunity to appear before this subcommittee this morning and would be glad to respond to any questions you may have.

[The prepared statement of Major General Small follows:]

Oral Summary
Railroads for National Defense
Senate Committee on Energy and Natural Resources
Subcommittee on Energy and Mineral Resources

19 January 1984

Good morning, sir. I am Major General Harold I. Small, Commander of the Army's Military Traffic Management Command which manages the Railroads for National Defense Program on behalf of the Department of Defense. We have been designated to respond to the Chairman's request to Secretary Weinberger for testimony on the importance of the Nation's railroads to national defense. I am accompanied this morning by Mr. Allen J. Dowd, my senior transportation engineer, and by Mr. Maurice E. LePera, who is Chief of the Fuels and Lubricants Division at Fort Belvoir's Research and Development Center.

We have prepared a three-part statement which has been submitted for the record. First, we have presented some detail on the purpose, scope, and accomplishments of the Railroads for National Defense Program. Second, as requested by the Chairman, we have included the procedures which we have developed with the Departments of Transportation and Energy for priority allocation of diesel fuel for railroads engaged in supporting a national defense effort, as authorized under the Defense Production Act. Third, we have addressed authority for funding the development of coal-burning locomotives, as requested.

The Department of Defense relies upon the railroads in meeting its peacetime, contingency, and mobilization missions. Large volumes of defense equipment, ammunition, and materials are moved by rail. Particularly noteworthy is the reliance upon the railroads for the movement of oversized/overweight equipment such as battle tanks, tank retrievers, howitzers, cranes, bulldozers, and ballistic missile components. The lack of a viable civil railroad capability could adversely impact defense installations and activities requiring rail service for completion of their assigned mission. In brief, the Nation's railroads comprise an essential link in the logistics chain needed to support any major defense contingency, such as the reinforcement of Europe.

Because of military importance of the railroad industry, we initiated a Department of Defense Railroads for National Defense Program. This program is designed to assure consideration of national defense requirements in plans, standards, and programs for the Nation's railway network. The Railroads for National Defense Program is closely coordinated with the Federal Railroad Administration of the U. S. Department of Transportation and with state and industry rail planners.

Because of a threat of nonavilability of fuels for the common carrier industry during a defense contingency, we have developed with the Departments of Transportation and Energy procedures for emergency priorities and allocations of fuels for common carriers supporting national defense, as authorized under the Defense Production Act. With regards to the development of coal-burning locomotives, such motive power to exploit the use of domestic fuels and reduce dependence on foreign sources would have obvious national defense benefits. It could minimize the need for invoking priorities and allocations procedures to carry out a defense mission, which could deprive the civil sector of a critical fuel source. While the Defense Production Act might be considered an authority also for the development of coal-burning locomotives, we believe that any locomotive developmental efforts belong within the purview of the Department of Energy as an issue which is not defense peculiar, but is commerce oriented and should be funded from civil sources.

Mr. Chairman, we appreciate the opportunity to appear before the Subcommittee this morning. We will be glad to respond to your questions.

A STATEMENT

ON

RAILROADS FOR NATIONAL DEFENSE

BEFORE

THE SENATE COMMITTEE ON ENERGY AND NATURAL RESOURCES
SUBCOMMITTEE ON ENERGY AND MINERAL RESOURCES

BY

MAJOR GENERAL HAROLD I. SMALL
COMMANDER
MILITARY TRAFFIC MANAGEMENT COMMAND
DEPARTMENT OF THE ARMY

ON BEHALF OF

THE DEPARTMENT OF DEFENSE

JANUARY 19, 1984

INTRODUCTION

Mr. Chairman, members of the Committee, I appreciate this opportunity to appear before the Committee to make a statement and answer your questions on the importance of the Nation's railroads to our national defense. I am the Commander of the Army's Military Traffic Management Command which is the Department of Defense single manager for land transportation. I am accompanied today by Mr. Allen J. Dowd, my senior transportation engineer, and by Mr. Maurice E. LePera, who is the Chief of the Fuels and Lubricants Division at the Fort Belvoir Research and Development Center.

As requested in your letter of December 9, 1983, to Secretary Weinberger, we have prepared a three-part statement. First, we have presented some detail on the purpose, scope, and accomplishments of the Railroads for National Defense Program. Second, as requested by the Chairman, we have included the procedures which we have developed with the Departments of Transportation and Energy for priority allocation of diesel fuel for railroads engaged in supporting a national defense effort, as authorized under the Defense Production Act. Third, we have addressed authority for funding the development of coal-burning locomotives, as requested.

DEFENSE PROGRAM

Because of the importance of the Nation's railroads to national defense, the Secretary of Defense designated the Military Traffic Management Command to represent the Department of Defense in the development of the Railroads for National Defense Program. The purpose and purview of the program is to assure consideration of defense requirements in civil transportation plans, standards, and programs for the Nation's railway network. The Railroads for National Defense Program is founded on the principle that it is in the national interest to ensure that national security requirements are duly considered in programs to improve the adequacy, efficiency, and financial viability of the rail system of the United States. It is vital for national defense that our rail system be responsive to the movement requirements of military forces and equipment.

Under our Railroads for National Defense Program, we have stressed analyses of defense needs for rail lines. The results of these analyses aid civil railroad planners--those working for rail carriers and those working for various levels of government--in considering the needs of national defense in their planning. The results of the analyses are particularly useful to civil planners in this era of railroad consolidations, mergers, and abandonments. The completed analyses have been furnished to individual rail carriers through the Association of American Railroads and to federal, state, and local rail planners through the auspices of the Federal Railroad Administration and the American Association of State Highway and Transportation Officials.

DEFENSE IMPORTANT LINES

Rail lines important to national defense include: mainlines, clearance lines, and connector lines.

The defense importance of mainlines is the strategic value of an integrated and interconnected system, rather than specific route importance. The mainline system's capability to provide for the expeditious movement of defense forces, materials, and equipment to mobilization and deployment sites throughout the Nation is of primary importance to the Department of Defense.

Clearance lines allow the shipment of oversize and/or overweight defense cargo. Examples of such shipments include battle tanks, tank retrievers, howitzers, cranes, bulldozers, ballistic missile components, and new major weapons systems under development. It is essential to national defense that clearance route capability be included in an integrated and interconnected mainline railroad system. Clearance routes are also required to provide access to those defense activities which are origins or destinations for oversize/overweight shipments.

Rail lines between the mainline system and defense installations are referred to as connector lines. The importance of connector lines is a function of relative use, the commodities being moved, the alternate modes of transportation available and, most importantly, the mobilization mission of the defense installation. Each of these factors is subject to change with time.

To identify and monitor defense rail requirements, we developed in 1976 the Strategic Rail Corridor Network (STRACNET), a 32,500-mile interconnected network of rail corridors important to national defense (see map). At our request, the Federal Railroad Administration designated a mainline within each STRACNET corridor. We then developed a Defense clearance profile to validate the clearance capability of lines designated for national defense. To complete the system, we have designated about 5,000 miles of connector lines to STRACNET for about 200 defense installations that need rail service to accomplish their missions. We have identified the maintenance condition and clearance capability of this network of STRACNET and connector lines, and we continue to monitor these characteristics for their adequacy to support national defense requirements. We work directly with the carriers to spot potential abandonments that could adversely affect the network, and we have been quite successful in minimizing the impacts on defense readiness.

OIL SUPPLY DISRUPTION

The Chairman asked that we include in our testimony provision for the continued operation of the Nation's railroads in the event of an oil supply disruption. For the purpose of this statement, we will assume that only indigenous oil supplies are available and a priority system is necessary to assure that defense-related rail movements are not interrupted.

The Secretary of Defense is charged under Executive Order 11490 with certain emergency preparedness functions. These include furnishing to the Department of Transportation military requirements for all forms of transportation including services, equipment, and facilities which would be required in the event of an emergency. We have developed a Contingency Response Program to coordinate our efforts with the Department of Transportation, other Federal agencies, and the civil transportation industry in providing priorities and allocations to resolve transportation service shortfalls during defense contingencies. This program includes specific procedures for obtaining priorities and allocations of transportation capacity under the authority of the Defense Production Act.

In addition to transportation services and facilities, the Contingency Response Program has a vital interest in the priority allocation of energy resources. The Department of Energy is included in the program in order to ensure effective coordination of Defense energy requirements during contingencies. They are responsible for developing and maintaining emergency priorities and allocation systems for energy in support of domestic national defense requirements. The Defense Production Act is the primary authority employed to facilitate defense needs. Under authority of the Act, we would be able to assure that rail carriers engaged in defense essential traffic would receive diesel fuel allocations for the movement of defense equipment, ammunition, and supplies.

LOCOMOTIVE DEVELOPMENT

In response to the Chairman's question of whether the Defense Production Act could be used to fund the development of coal-burning locomotives, the Act doesn't provide for funding such development per se; however, it does provide for the procurement of materials for the national defense. It also provides for loans to expedite production of materials for the national defense, including the development of technological processes. The Act can only be used to the extent of available funding which has heretofore not been appropriated or allocated for this purpose.

We do not consider the development of coal-burning locomotives to be a defense peculiar function, but rather one that is oriented toward alternate uses of energy in support of trade and commerce. Research and development activities associated with coal-burning locomotives are within the purview of the Department of Energy. You have heard testimony earlier from the Department of Energy representatives of their efforts to assist industry in this regard. For these reasons, we believe that questions concerning authority for funding the development of alternate energy sources for locomotives should be addressed to the Department of Energy and their existing research and development authorities used in lieu of the Defense Production Act.

SUMMARY

In brief, the Nation's railroads are an essential national defense asset. While we do not believe that the Defense Department should have a direct role in the development of coal-burning locomotives, energy self-sufficiency resulting from such development would have obvious public interest benefits, including national defense. We will be glad to respond to your questions.

Senator WARNER. Very helpful testimony on behalf of the Department of Defense. As you know, as a member of the Senate Armed Services Committee, I have considerable familiarity with the defense budget and its billions and billions of dollars which we are correctly devoting to national defense today and then examine the vulnerablity of that whole structure to energy. I am gravely concerned. World War II, when I was but a sailor, I remember vividly the line of naval ships as far as the eye could see stretching to the horizon, fueled by oil from the United States of America. We had very little dependence on foreign sources. We had an incredible national defense organization which saved the world in World War II. Likewise, Korea, minimum dependence. But since that time in history we have become increasingly dependent on foreign fuel sources, as the testimony indicates today. I want the American public to clearly understand that the investment they are putting into our national defense is highly dependent upon the availability of energy at the critical time and the Department of Defense is carrying forward many plans to defend this Nation, our allies—and collectively, both, which will call on energy resources in direct competition to the civilian community. The extent to which we can take any major segment of our economy and make it less dependent on foreign import and energy sources, the better off we are in terms of our national defense.

General, there were two questions that I had. In your testimony you mentioned that the National Defense Production Act might be considered as the authority also for the development of coal burning locomotives. I realize you are not advocating this approach, but could you inform the committee how the Defense Production Act might—and I say might—utilize the development of a coal burning locomotive?

Major General SMALL. Mr. Dowd will answer that question.

Mr. DOWD. Its our understanding that there are sections of the Defense Production Act that provide authority for loans to expedite production of materials that are important to national defense. We are advised by general counsel that those loans could also apply to the development of the technological process that's necessary to develop those materials.

Senator WARNER. The subcommittee will explore that further. Gentlemen, could you explain the Railroads for National Defense Program you have developed with the Federal Railroad Administration and the U.S. Department of Transportation?

Major General SMALL. Well, basically what we have done is we have identified in coordination with those agencies about 32,500 miles of network, rail networks, that we feel are necessary for the mobilization of the Nation should we have to go to war. It includes main lines as well as connecting lines to some 200 defense installations in our country which require rail service. In a peacetime environment, we ship right now roughly 2 percent of our cargo by rail. That would increase to approximately 20 percent in total mobilization. So we felt it very necessary to develop a program which would assure us that mode of transportation should it be necessary. That would include not only the deployment of the active forces but also the mobilization.

Senator Warner. Yesterday I visited the railroad defense line operated by the people up here in the Richmond area. As a part of that, I was amazed at the very extensive rail yards—siding, switching, even a roundhouse exclusively required for the servicing of the locomotives and the operating equipment needed for the defense agencies supplies. It brought home to me the defense reliance on this.

Thank you very much, gentlemen.

Mr. Morriss, we have heard of you for a long time. The subcommittee is at last grateful to meet you and hear from you. You are recognized by your peers as one of the eminent deans in this field. Thank you for attending today.

STATEMENT OF KENNETH C. MORRISS, VICE PRESIDENT FOR ENGINEERING, CHESSIE SYSTEM RAILROADS, CLEVELAND, OH

Mr. Morriss. I feel flattered by the comments about being the dean, however, I must say to you that there are many engineers, some of them in this room including Steve Ditmeyer, my associate from Burlington Northern.

Senator Warner. Do you want him at the table, here?

Mr. Morriss. No, he will come later. Who are all more eminently qualified in this area. I would suggest that probably the term should be dedicated proponent of the development of the coal fired locomotive. The Chessie and Seaboard System Railroads are the two railroad units of the CSX. Since I have been the officer responsible for the development of the proposed joint venture to build the prototype of a coal-fired locomotive by American Coal Enterprises, I am testifying today on behalf of the two railroads and our parent corporation, CSX.

I have a prepared statement that has been submitted for the record and, with your indulgence, I will just highlight some of the points that I would like to make.

First, I'd like to say or to emphasize that the strong interest that CSX management both on the railroad and at CSX of which you are already well aware, in the development of coal as an alternative fuel for locomotives. Our railroads consider themselves to be very much a part of the coal industry. Nearly 30 percent of our revenues of CSX come from the moving of coal. On Chessie, that percentage rises to in excess of 55 percent of our revenues comes from coal. And we strongly support the increased use of coal. We have an important stake in that.

Now my own background is that I have spent more than 42 years with the Chessie System Railroads, beginning as a land surveyor in the location of railroads in the coal fields back about the time of the beginning of World War II. And I served in both the operating end of the railroad and in the engineering department.

Senator Warner. You will permit me a personal observation. I came out of World War II a sailor and went to Washington and Lee University which had a department of engineering that I joined. While there I took courses in land survey for rail systems and did some field work in the valleys of Virginia. I have a modest knowledge of what you have done.

Mr. MORRISS. Fortunately or unfortunately, they don't teach the same subjects today in the engineering school and its probably to our advantage. So obviously I have gone through the transitionary period between the operation of steam locomotives in the 1940's and the 1950's and into the diesel electrics that we have today and, of course, we are continuing to buy diesel electric locomotives today. Some are being delivered to us this week from one of the major manufacturers.

The main point that I'd like to make is the energy crisis of 1974 and 1979—the crisis at both times—highlighted in a very dramatic and expensive way the uncertainty of the future supply of diesel fuel. We are all aware of the impact of escalating fuel oil prices, which dramatically increased the operating costs of the railroads. Very suddenly we went from an era of energy abundance to an era of energy scarcity. The energy crisis gave a very healthy shock to our thinking. And while we are now in this period of energy glut or temporary whatever they want to call it, we must face an uncertain future. Its there in front of us. The energy crisis has become permanent.

Now one alternative, of course, was electrification which was studied by the FRA and well documented in our committee hearings. It proved to be too expensive for Chessie. Capital costs too high and not economically feasible. So while electrification is technologically feasible, it just doesn't make economic sense.

In 1981, Chessie began looking at the possibility of developing some kind of coal fired locomotive in connection with the Burlington Northern and American Coal Enterprises.

A considerable amount of time and effort was devoted to this project by the railroad participants and our preliminary assessment was that the ACE 3,000 represented a first generation coal fired locomotive that could be commercially available in 2 or 3 years in limited numbers. And operated on our property in limited numbers with a high internal rate of return.

Unfortunately, this project did not come to fruition and we find ourselves going down the road searching for other alternative fuels, other improvements in existing locomotives, all of which have been documented before you and I don't think that I should take your time to elaborate upon them.

But the uncertainty as to the future supply of diesel fuel and its high costs indicates a continuing need to develop alternatives to the diesel electric locomotive. And this we must do. It was interesting to note that the FRA Administrator talked about the railroad suppliers in his fine presentation just a few moments ago. I do not really believe that our locomotive supply industry shares the concern that was expressed by the FRA Administrator and many of the other witnesses before this committee. I think that we need to emphasize that fact.

In conclusion, Mr. Chairman, let me say that CSX and its railroads believe that the best interests of the railroad industry will be served by continuing to explore the development and possible use of the coal fired locomotive. Our own good faith commitment to the ACE project demonstrates that the private sector will support with its dollars such development.

We believe the Government's role should be to encourage and supplement the efforts of the private sector and through adequate research and development funding to continue the search for improved technology based on coal. I firmly believe that as long as the potential threat in the supply of oil remains and there is danger of another shortage, or sharp increase in oil prices, there will be strong economic incentive to the railroads to pursue the efforts they have begun to find an economic means of using coal as a source of fuel. I thank you for allowing me to testify.

Senator WARNER. Drawing on your knowledge, and I don't wish to invade the corporate privacy of CSX or your partners in that venture with ACE—drawing on your general knowledge, what form of inducement should be forthcoming from the Federal Government to overcome what appears to be some lethargy in your industry to move out and tackle this problem?

Mr. MORRISS. I am not certain that I am really qualified to answer that question. It's probably out of the realm of my expertise but certainly our companies are not looking for a handout of Federal dollars. We would like to have the support, however, of the people like yourself and I really don't know how that might be handled. Whether it would be the Department of Defense or whatever.

Senator WARNER. That's my problem to solve, hopefully, along with my colleagues in Congress. This record is carefully documented with statements such as you have made and we expect to move forward with a national program to explore the potential technical and economic feasibility of coal on the rails.

Mr. MORRISS. It would seem that its going to take a combination of a number of railroads going together along with some supplier or manufacturer. To repeat, the major manufacturers of locomotives today have little incentive to put their dollars into another way or method of manufacturing locomotives.

Senator WARNER. Let the record reflect that. Perhaps I am unfairly taking you from the field of your engineering, but based on your engineering knowledge, is this technically feasible?

Mr. MORRISS. Certainly it is technically feasible.

Senator WARNER. Within a timeframe of 5 years or less for a prototype.

Mr. MORRISS. Well, there are various steps.

Senator WARNER. To a single or two operating prototypes.

Mr. MORRISS. All we need is the dedication and the effort.

Senator WARNER. And the technicians in the United States can create this engine?

Mr. MORRISS. I have no doubt about it.

Senator WARNER. And it will be environmentally acceptable. Now, that's just a general observation but I have been told it will be environmentally a step forward from the existing diesel today without compromising too many of the economic advantages?

Mr. MORRISS. To be marketable, it would have to be. And the problems enumerated—the potential problems enumerated by the FRA Administrator—concerning the effect on traffic conditions, and so forth, do not appear to me to be of as a critical nature as some of the other design problems of the combustion of coal and the design of the locomotive itself. I tend to believe that the track problems will have a lower priority.

Senator WARNER. And they can be resolved.

Mr. MORRISS. Yes.

Senator WARNER. With the sparse knowledge of engineering and based on the experience in the Department of Defense that I have, as one watches technological development there is a legitimate reason for industry not to leap to one threshold of technology recognizing that in a very few years there will be another threshold which is considerably improved. The funds expended to achieve a prototype on threshold A will not be justified when technology moves to B. Do you see that?

Do we now have sufficient R&D performed to know what we can achieve by way of state of the art so that 5 years from now we wouldn't look back and say that's wasted time? I'm sure you could articulate this better than I because this is your area, but you know the problem.

Mr. MORRISS. I know the problem. I visualize it as being comparable or parallel to the computer industry. The technological advances may come so quick that it will make the first efforts of the development and design of a coal-fired locomotive, whatever it may be, obsolete in a short time. That is one of the problems, we acknowledge that. But that is something that, obviously, has to be done because we cannot go from the bottom to the top in one step. So there are quite a number of research avenues that are being explored although I must admit I feel progress sometime is extremely slow.

Senator WARNER. I am pleased to hear that because I really think we need a breadboard model operating today on some part of our rail system to prove or disprove the technical and economic considerations.

Mr. MORRISS. Senator, that was basically one of the things that we considered when we supported the ACE project in its initial inception.

Senator WARNER. Now, of course, this record contains extensive testimony about ACE. Do I understand you to inform the committee that the project is now on the shelf?

Mr. MORRISS. It might be, as described in aviation history, as in a holding pattern.

Senator WARNER. A holding pattern. All right. To the extent that we don't invade the privacy of your corporate affairs, can you inform the committee as to your reason for the holding pattern?

Mr. MORRISS. It is my belief that the combustion manufacturer or manufacturer of combustion systems was involved with us in the project probably reached the conclusion that there was little manufacturing opportunity for them.

Senator WARNER. On a long-term basis?

Mr. MORRISS. Yes; because quite frankly the domestic U.S. facilities capable for production of locomotives and so forth belonged to the competition. And they probably felt they couldn't compete. Now, I'm drawing a conclusion for something that I am not completely knowledgeable in.

Senator WARNER. The subcommittee expresses its appreciation to you for taking your valuable time to participate in this hearing. Thank you.

STATEMENT OF STEVEN R. DITMEYER, DIRECTOR, RESEARCH AND DEVELOPMENT, BURLINGTON NORTHERN RAILROAD CO., ACCOMPANIED BY RONALD REIMANN, DIRECTOR, GOVERNMENT AFFAIRS

Mr. DITMEYER. Thank you, Senator, it is a pleasure to be here in Richmond in the warm and mild weather that we're encountering here today.

Senator WARNER. Would you please introduce your colleague?

Mr. DITMEYER. Yes; with me today is Ronald Reimann who is director of government affairs for Burlington Northern Railroad.

Senator WARNER. He is well-known and respected in the Halls of Congress.

Mr. DITMEYER. We are going to attempt today to answer the questions that you have raised about the potential for the development and deployment of coal-fired locomotives on American railroads.

The BN is the longest railroad in the United States and, as such, is one of the largest consumers of diesel fuel in the country. In 1983, our diesel fuel bill was over $500 million.

Senator WARNER. Incidentally, if I'm correct—I don't presume to know your entire rail lines—but you're somewhat remote from diesel sources, aren't you?

Mr. DITMEYER. Well sir, our line stretches all the way from Vancouver, BC, down to Houston, TX. So we touch on various refinery areas, but again a large central part of our system is away from our sources. But because our fuel bill is so large and because the price of fuel is so important to us we have for some time been investigating a number of alternative energy sources that we might use. Among these alternatives are coal, electricity, natural gas, methanol, and heavier petroleum fuel fractions. Diesel fuel has been subject in the past to radical and unpredictable variations in both price and availability in an uncertain world market.

The prospect of using coal as a fuel is one that is particularly promising to BN. The availability of coal at a price per unit of energy well below that of diesel fuel makes it a very attractive option for us. There are several proposed designs for a new generation of coal-burning locomotives that would use the latest microprocessor controlled industrial boiler technology to obtain more complete combustion of coal, thereby raising efficiency and reducing emissions to levels no greater than that of diesels. Old coal-burning locomotives has a thermal efficiency of around 5 percent; the new should have around 15 percent.

Senator WARNER. Let me interrupt you there. In other words 5 percent of usable Btu's in coal is directly transmitted to the rail?

Mr. DITMEYER. That is correct.

Senator WARNER. 25 percent is lost to the atmosphere and otherwise?

Mr. DITMEYER. That's right. Much of the black smoke of old steam locomotives was unburned carbon coming out the stack. There were other thermal losses.

Senator WARNER. And the prototypes that you have analyzed to date would go from 5 to 15 percent?

Mr. DITMEYER. That is what we believe is feasible, yes, sir.

Senator WARNER. And what is the diesel?

Mr. DITMEYER. Diesel is about 30 percent.

Senator WARNER. So in the area of thermal efficiency the diesel locomotive has a distinct advantage over coal-fired locomotives.

Mr. DITMEYER. Oh, yes. But the point that I guess we make is that because coal is so much cheaper than oil, the new generation coal-burning locomotives are an economically attractive proposition for us even with somewhat lower efficiency than diesel and even if more expensive to buy and even potentially more expensive to maintain.

Senator WARNER. Particularly when you have so much coal owned by and in close proximity of your rail system.

Mr. DITMEYER. Yes, but I guess we view our ownership of coal almost as a sideline. The fact of the matter is we have access to it and access is the key. It's the key for us.

Senator WARNER. Coal is right along you entire rail?

Mr. DITMEYER. Yes, sir. We believe, though, that it would probably take more than 2 years to get coal-burning locomotives opeational and we think on the order of five, but that should be easy.

Because we are aware of the economics of coal, nearly 1 year ago we negotiated an agreement with the General Electric Co. whereby they would conduct research into coal-fired locomotive technology on our behalf. We are quite pleased with GE's results to date and we are glad that the Norfolk Southern has decided recently to join in the research program at GE.

For a portion of 1983, Burlington Northern was a member of a partnership which Mr. Morriss mentioned including Babcock & Wilcox, Chessie, and American Coal Enterprises. The withdrawal of Babcock & Wilcox from the partnership, however, caused us to question the ability of the partnership to actually fabricate the prototypes and so, consequently, we too withdraw. BN has concluded that the work at General Electric probably offers the best near-term approach for bringing coal into use on our railroad. Because GE is one of the two major locomotive manufacturers, it means that we on the railroad do not have to get involved ourselves with arrangements for the manufacturing process.

We also sponsored a study of a longer term, advanced technology called alkali metal thermoelectric converter. An AMTEC device would be able to convert heat, from a source such as coal, directly to energy with no moving parts. This technology, which is an outgrowth of the space program, though, is not expected to be fully developed for railroad application until the late 1990's.

Electrification represents another way that railroads could make use of coal for powering trains. Widespread in Europe and Asia because of high petroleum prices and because of government financing of railroads, it exists in the United States only on the Northeast corridor, some commuting lines, and some private coal-hauling railroads. Project financing has always been the problem in this country. BN studied electrification again last year but concluded that it was not economical at this time on our lines. It may, however, be justified on other lines of other railroads.

Senator WARNER. Could you share with us how close your calculations came to making it economically feasible?

Mr. DITMEYER. I was not a member of the study group so I have to go by recollection. The problem was decreases in, recent instances, in diesel fuel prices. The fact that we now have an agreement with the Chicago Northwestern for the Northwestern gaining access to the Powder River Basin has meant some forecast of decrease in our coal traffic below what we had previously expected. Plus some other operational changes on our system with our existing diesel locomotive meant that we were a fair distance away from having it be economically attractive.

Senator WARNER. So there's some extraneous factors and parts to your decision not to electrify your system or to move rapidly to a coal-fired locomotive?

Mr. DITMEYER. That's right. As I mentioned, we are looking beyond coal in our search for alternative fuels. Burlington Northern has the only locomotive in the United States capable of running on natural gas as well as the only one capable of running on methanol. Both underwent stationary testing in 1983, and we expect to run over-the-road tests in 1984. Natural gas is the most economically attractive of these options because of lower cost per unit of energy and low conversion costs. Methanol is interesting, however, because it can be produced from coal. If world-scale coal-based methanol plants were to be built in this country in the next decade or so, methanol could become a very attractive railroad fuel.

I should point out to you that Burlington Northern does not believe that coal will ever completely displace diesel fuel on its system. As I mentioned, we stretch from Vancouver to Pensacola. While there are a number of high-density portions of our railroad on which the use of coal might make a great deal of economic sense, there are also portions of our railroad that have a low-traffic density or are too far away from coal fields for coal to be a viable fuel. Also, diesel fuel has a fairly uniform price throughout our territory and throughout the country; its price varies probably no more than 10 percent from location to location. Coal, on the other hand, is very expensive to haul and so consequently coal will be attractive as a railroad fuel largely on those lines that radiate out of the coal fields.

Railroads face several problems in converting to coal-fired locomotives. An individual railroad is a large enterprise with major facilities located over thousands of miles of territory. Consequently, the prospect of significant changes in its operations involves profound investment and operating decisions. However, these problems are being ameliorated by the deregulated railroad environment in which we find ourselves. I personally believe that, compared to the past, the time required to introduce new technology on railroads will be drastically shortened in the future because of deregulation and the continuing pressure of the transportation marketplace on railroads to keep their operating costs down.

There are a couple of potential impediments to the development of coal-fired locomotives which are in the realm of Government responsibility. The most important would be emission standards. The EPA and others have periodically spoken of issuing locomotive emission regulations. At present, there are none. Designers of a new generation of coal locomotives would need to know if emission standards are going to be issued and, if so, what they would be. Clearly, those standards would have a significant influence on the locomotive design.

Another area of concern—I hesitate to call it an impediment—is the Federal Railroad Safety Standards still on the books governing the design and inspection of steam locomotives. These standards reflect a technology of the 1940's and 1950's, not the 1980's, and therefore would have to be changed to accommodate the new generation coal-fired locomotive.

Burlington Northern has structured its locomotive R&D Program on the basis of an economic and technical analysis of competing fuels and propulsion systems in the marketplace. Consequently, we are not seeking assistance from the Federal Government, and we certainly do not think that such involvement is necessary for the railroad industry to make a decision in the public interest. We do acknowledge that to achieve some other end, such as greater national energy independence, such assistance might be considered by the Congress. In that event, we would be pleased to comment on any proposals you might care to have us consider.

Mr. Chairman, we congratulate you for holding these hearings on what we believe to be a most important subject, and we appreciate the opportunity to be here with you.

Senator **Warner**. I appreciate that and your very informative and precise contribution to this record. This record is replete with solidly documented reasons for this Nation to restore this technology. Sometimes we have to find out what is the best way we can get it done. I thank you for coming down with this testimony and to offer your assistance. We may well call on you formally or informally to do that in the future. If you at some point in time wish to formally or informally communicate with me on how to get it done, I leave it to your discretion.

Mr. **Ditmeyer**. Thank you, sir.

Senator **Warner**. Thank you very much.

We now have a panel discussion: Dr. J. Gordon Davoud, president, D-Cycle Power Systems, Inc., Richmond; Mr. Daryl A. Matthews, president, American Synthetic Fuels Corporation, Richmond; and Mr. William Kuntz III, on behalf of Westrail Corporation and Wolfpack Electronics, Lake Placid, NY.

STATEMENT OF DR. J. GORDON DAVOUD, PRESIDENT, D-CYCLE POWER SYSTEMS, INC., RICHMOND, VA

Dr. **Davoud**. Thank you, sir. My name is Gordon Davoud. I am an officer in a small high-tech company here in Richmond which has had a number of patents on advance steam cycles. In order to present a credential that we are not simply talking from strong desire, we have had some experience with Government contracts. Our credentials include three, one of them on an in-depth research on stationary steam engines for the Department of Defense; a technical-economic feasibility study for the Maritime Administration of the Department of Commerce for the application of the D-Cycle to large ship propulsion; and a technical study for the Department of Energy for a steam Stirling engine.

We have designed, built, and run a reciprocating engine using the D-Cycle, and the cycle is applicable to electric power generation. It is a natural for a steam locomotive.

Senator WARNER. Natural what, sir?

Dr. DAVOUD. A natural for a steam locomotive. We believe the following, and are prepared to support our believe with engineering figures.

First, a steam locomotive of modern design would have overall thermal efficiency, from fuel to wheels, comparable to a diesel-electric locomotive. The D-Cycle could be used, though it is not essential to an efficient design. It is, however, more efficient than the usual steam cycle.

Second, we are thoroughly familiar with steam system developments, especially as they relate to steam automobiles. There have been major improvements in technology, material, design, and concepts, which can be used to great advantage. There is a point I want to particularly make. Much of this work has been developed by small companies and by individuals. The best modern steam car in the world was designed, financed, and built by two individuals, father and son, who own a small engineering firm. The design incorporates two notable innovations which we or anybody else making reciprocating engines would certainly use.

Third, the combustor-boiler can be built, using known technology to meet the twin requirements of high efficiency and rigid emission standards.

Fourth, the fuel cost would be about half that of the present diesel electric locomotive in general use.

Fifth, fuel feeding and handling can be fully automated.

Now, how much would it cost to develop a prototype? A figure of from $50 to $70 million has been mentioned. We believe it, especially the higher figure, is reasonable. We also know small companies can do it for far less cost than large ones.

The incentives to railroads and coal mining companies to make the changes back to coal are obvious and very large; we've heard all about them all day: for the railroads, annual savings of about 50 percent in fuel costs, and increased usage of coal of about 20 million tons to the mine owners.

Sir, I think that anybody that looks at the figures would find that a saving of $2 billion right off the top of the cost to the railroad represents considerably more money than they make these days.

Senator WARNER. A very valid observation.

Dr. DAVOUD. They do, indeed, have a powerful incentive. However, I must say—and everything I've heard today bears out what I think—however attractive in concept, the idea of a financial package from a consortium of the private sector seems to us to be unrealistic.

To us, it seems more practicable for the U.S. Government to set a very limited objective: to issue a number of contracts for a conceptual design, followed by an engineering design, for a coal-burning steam locomotive. In this way, the ideas which are so often generated by small operations or individuals, could be given an equal opportunity with those from large companies.

At that point, the best design could be "sold" on its merits to the private sector by the designer. This is an approach we favor. It has to be beneficial to the overworked bottomline, which must figure in every successful company's view into the future.

And I would point out again that the steam locomotive business that withered on the vine was not the steam locomotive companies that make diesel locomotives at all, it was somebody else. And the way to get a successful steam locomotive made now in my opinion is not to go to anybody buiding locomotives, but to somebody who wants to do business. And I think that would be perfectly feasible if you had a good design and you could then sell it on its own financial merits which, in my opinion, is the only way to get things done in this country.

Any way you look at it, the design capability and the engineering technology to make a successful steam locomotive exist right here in Richmond. There's a large engineering company in Richmond whose premise is just to make a locomotive, they'd be delighted, in fact, if they can make money doing it. The apalling thing about this, it denies the steam locomotive business—in 1944, there were over 40,000 people employed at a company in Philadelphia; 44,000 people. Today there are none. It occupied an extremely large area—you probably saw it, sir, during the war. I didn't. My own family in Canada were railroaders in Canada, part owners in two locomotive companies. They went down the slot just the same way. They thought that nothing could ever happen. And they would be delighted to get back in the business.

There's one other thing I would say. The study of this subject has already been made by the Jet Propulsion Lab as described in a previous session by a staff member. While we retain the highest respect for the worker in the lab, we do not agree that the future development of the steam locomotive to be cast in concrete. By combining it with the new drive and chassis of the current diesel electric locomotive and the use of classic diesel motor, electric generator, electric motor drive, and a propellant—a real advantage of the reciprocating engine is its large starting torque—you don't need such an elaborate transmission. This offers an alternative to the engine generator electric motor drive. It can be so economical and so effective, not like what plagued the old steam locomotive.

We have heard some of the witnesses today talk about the pounding of the reciprocating drive. That could be overcome by design but its more or less the locomotive that existed in the past. And I know for a fact that every time they take out that Union Pacific big boy, the world's biggest steam locomotive, the track engineer had a fit since it tended to tear up the track.

Senator Warner. I know the engine well. And for those who might be in attendance today who have a romantic feeling for the rail, and I am one, it is a colossal thing to observe in operation. I even have a model of it on the shelf in my library.

Dr. Davoud. So I think this offers an alternative for the design based on an electric carrier, an electric motor drive which is certainly a way for a small company. However, if this thing is financed by the Government, I think it would be a great mistake to just shell out a lot of money to one big company to do it because I think they will lose a whole lot of contributions that could come from the small companies.

[The prepared statement of Dr. Davoud follows:]

D-Cycle Power Systems, Inc.

STATEMENT MADE BEFORE SENATOR JOHN W. WARNER
SUBCOMMITTEE ON ENERGY AND MINERAL RESOURCES
"REINTRODUCTION OF COAL AS FUEL FOR RAILROAD LOCOMOTIVES"

Statement made before third Public Hearing, Monday, January 9, 1984, Richmond, Virginia, by Dr. J. Gordon Davoud, President, D-Cycle Power Systems, Inc., 9019 Forest Hill Avenue, Richmond, Virginia 23235.

The D-Cycle is a high efficiency steam system. The application of the system to steam locomotives has been close to our hearts - and minds - for some time. The opportunity to express our opinions at this public hearing, sponsored by our far-sighted senator, is welcome indeed, to put it no stronger.

So no one is in any doubt, we are 100% in favor of the idea. For the next few minutes, let me tell you why.

This company's credentials include three United States Government contracts for in-depth research on stationary steam engines from the Department of Defense; a technical-economic feasibility study from the Maritime Administration of the Department of Commerce for the application of the D-Cycle to large ship-propulsion; and a technical study for the Department of Energy for a steam Stirling engine.

We have a conceptual design for a wood-burning steam powered off-shore fishing trawler.

We have designed, built and run a reciprocating steam engine using the D-Cycle, and the cycle is applicable to electric power generation. It is a natural for a steam locomotive.

We believe the following, and are prepared to support our belief with engineering figures.

1. A steam locomotive of modern design would have overall thermal efficiency - from fuel to wheels - comparable to a diesel-electric locomotive. The D-Cycle could be used, though it is not essential to an efficient design. It is, however, more efficient than the usual steam cycle.

2. We are thoroughly familiar with steam system developments, especially as they relate to steam automobiles. There have been major improvements in technology -- material, design, and concepts, which can be used to great advantage. Much has been developed by small companies and by individuals. The best modern steam car in the world was designed, financed and built by two individuals, father and son, who own a small engineering firm. The design incorporates two notable innovations.

3. The combustor - boiler can be built, using known technology to meet the twin requirements of high efficiency and rigid emission standards.

4. The fuel cost would be about half that of the present diesel electric locomotives in general use.

5. Fuel feeding and handling can be fully automated.

Now, how much would it cost to develop a prototype? A figure of from $50 to $70 million has been mentioned. We believe it (especially the higher figure) is reasonable. We also know small companies can do it for less cost than large ones.

The incentives to railroads and coal mining companies to make the changes back to coal are obvious, -- and very large; for the railroads annual savings of about 50% in fuel costs, and increased usage of coal of about 20 million tons to the mine owners.

However attractive in concept, the idea of a financial package from a consortium of the private sector seems to us to be unrealistic.

To us, it seems more practicable for the United States Government to set a limited objective,--to issue a number of contracts for a conceptual design, followed by an engineering design, for a coal-burning steam locomotive. In this way, the ideas which are so often generated by small operations or individuals, could be given an equal opportunity with those from large companies.

At that point, the best design could be "sold" on its merits to the private sector by the designer. This is an approach we favor. It has to be beneficial to the overworked bottom line, which must figure in every successful company's view into the future.

Any way you look at it, the design capability and the engineering technology to make a successful steam locomotive exist right here in Richmond.

D-Cycle Power Systems, Inc.

ADDENDUM TO STATEMENT MADE BEFORE SENATOR JOHN W. WARNER
SUBCOMMITTEE ON ENERGY AND MINERAL RESOURCES " REINTRODUCTION
OF COAL AS FUEL FOR RAILROAD LOCOMOTIVES" THURSDAY, JANUARY 19, 1984.

A study of this subject has already been made by the Jet Propulsion Laboratory, and described in a previous session by a staff member, Dr. Sydney Liddle.

While we retain the highest respect for the work of the Laboratory in any sphere, we do not agree that the future development of a steam locomotive should be, so to speak, cast in concrete by confining it to the presently used drive and chassis of current diesel-electric locomotives, and to the essential prime mover - electric generator - electric motor drive which propels it.

A real advantage of the reciprocating steam engine is its large starting torque at low engine speeds. This offers an alternative to the engine - generator - electric motor drive which can be so designed as to control the defects which plagued the traditional steam locomotive. An opportunity to present this alternative should certainly be included in any program.

Senator **Warner**. I certainly admire your spirit and willingness to come in here and take your valuable time to make this important contribution. Philosophically, I am of the belief that the private sector ought to do these things. And, indeed, my recollection is hazy but I recall the Federal Government developed an atomic powered merchant ship one time and I think it was in the merchant fleet. I think the thing is in drydock, am I not correct?

Dr. **Davoud**. Yes.

Senator **Warner**. And then, when I was Secretary of the Navy, I was quite familiar with the use of nuclear power and a strong advocate of it. Indeed, throughout my career in the Senate, I advocated nuclear propulsion for our Navy ships to a limited extent. We have, fortunately, in the past 5 years seen an enlargement of contracts for nuclear propulsion. Its worked and its been safe but I am so fearful of having the Government sit down and build this engine. But maybe that fear will disappear upon some reflection. I'm not going to give up on this project. I assure you of that. I'm not going to give up. I may be caricaturized by the cartoonists as Don Quixote, but I am so convinced that this engine is feasible and the record bears this out and people like yourself reinforce my own conviction.

We will now hear from Mr. Matthews.

STATEMENT OF DARYL A. MATTHEWS, PRESIDENT, AMERICAN SYNTHETIC FUELS CORPORATION, RICHMOND, VA

Mr. **Matthews**. Good afternoon, Senator, I appreciate the opportunity to testify and be here simply because I felt that the work that we are doing at American Synthetic Fuels would provide the locomotive with a synthetic fuel and I detailed this strategy as an attempt to foster the infrastructure of creating energy independently in the United States.

During the next 5 months, the U.S. Synthetic Fuels Corporation will be soliciting proposals to assist a project for producing coal water fuel for use in industrial fuel burning facilities. As a result of this, there has emerged the framework of a Virginia strategy and, of direct interest to you, a body of energy strategy for financing the construction of a prototype locomotive.

Last month, the executive director of the Virginia Fuel Conversion Authority summarized the authority's fundamental coal strategy in nine words: "Virginia coal is just right for coal water mixtures." Through the promotion of Virginia produced coal water mixtures, economies can be substantially achieved to mitigate and neutralize any negative impacts of interruption of foreign oil supplies during national emergencies, and remove our national railroad system from dependence on imported oil.

Coal water mixtures with small amounts of chemical stabilizers are projected to be about 20 percent less expensive than No. 6 fuel oil. Boilers capable of burning both coal and oil can be inexpensively converted to fire coal water mixtures. The potential for this fuel, however, is measured in the 100 million tons of coal range.

This morning I would like to spell out for you, in as much detail as time permits, the basis for our strategy, the nature of its components, and the conclusions that are pertinent to the subcommittee.

It is appropriate to do so here this morning because burning fuel derived from coal has been accorded a high priority rank, and a first priority within that program has gone to converting the Nation's locomotives to coal. Being first among first, places enormous responsibility on all of us in the coal conversion business. It is a recognition long awaited, but now awarded it must be fully discharged.

The foundation of our strategy lies in the fact that this Government cannot afford nor can any government afford an overhaul of its grand strategy every 4 years. Foreign policy and defense planning must be conceived and executed around certain basic principles and objectives. In the case of the United States, we see these as the achievement of energy security being essential to the health of the national economy, the well-being of our citizens and the maintenance of national security as embodied in the Energy Security Act, and the Virginia Fuel Conversion Authority Act. Second, in order to respond to those actions that occur outside of the United States which could result in the termination or reduction of the availability of strategic and critical materials, including energy which would adversely affect the national defense preparedness of the United States which is essential to national security. It is also necessary and appropriate to assure domestic energy supplies for national defense needs.

Senator **Warner**. That is a very good point. When I spoke about the enormity of the expenditures each year for Americans to make for defense and the dependability of that structure being created, be it airplanes, tanks or ships, the dependency on fuel is tremendous.

Mr. **Matthews**. Third, to use these acts to help private enterprise construct facilities for the production of snythetic fuels, particularly coal. And our proven reserves of coal in Virginia are topping 10 million tons, which would enable us to run a very effective synthetic fuels industry. These basic purposes, plus a decade of experience, on our part, provide the foundation for our coal strategy.

Planning has been completed for the implementation of an industrial project in southwestern Virginia which will provide a new annual market for approximately 10 million tons of Virginia coal. To a large segment of the mining community which suffers from an unemployment rate estimated to be over 28 percent resulting from massive and continuing reductions in coal sales in past years, project implementation would mean at least partial recovery in the immediate future.

Relevant to the existing Virginia coal community economic problems, new technological advances new available permit immediate construction and operation of relatively small synthetic fuel production facilities at industrial mine locations. Each of these facilities will process approximately 900,000 tons of coal annually, converting the coal to diesel fuel, that is 25-percent less expensive than petroleum based diesel fuel. Key planning factors germane to the construction and operation of these units have been provided to the Virginia Fuel Conversion Authority. I would encourage a meeting with the Governor and you on this project whereby you could learn of the steps Virginia synfuels project have taken on disseminating this data and had limited discussion with the board of authority to implement this technology.

Senator **Warner**. It would be a plesant conversation.

Mr. **Matthews**. While such an action could ostensibly weaken the financial viability of converting all of the Nation's locomotives to coal in the long term, no legal, moral or technical reasons exist which could mitigate against their immediate involvement. As a matter of fact, in view of the current unemployment situation in western sectors of the Commonweath, I would think their involvement is already long overdue.

Today, the politics of oil, the limited world supply, and the fact that the Soviet economy is consuming increasing amounts of energy at progressively higher cost provide a potential for superpower confrontation. Terrorism, space policy, nuclear proliferation, and regional instabilities all add uncertainties as we try to plan for the next generation. These pluses and minuses lead us to some conclusions in planning for today and the future.

Senator **Warner**. I would make another observation as one who has participated in three wars and been a student, lifetime student, of the misfortunes and origins of wars that have been fought for many reasons, you go back to the origins of the wars and find that energy is emerging as one of the pressure points. Be it between superpowers or the Third World, which is trying at achieve a level of lifestyle which approaches only the bare minimum that we have in our own culture and society. You've made a second very astute observation.

Mr. **Matthews**. How is this to be done? First, each of our planned catalytic conversion units are to be located at mines to be selected primarily upon one, the chemistry and the amount of waste coal available for conversion at one group of mine sites, two, the chemistry, amount and type of production coal to be converted at others, and three, the guaranteed return from both. These selection criteria, particularly three above, are biased, and properly so, by the Virginia coal water mixture project objectives.

While the same selection criteria would apply should individual mines become involved, their priorities would differ. As an example, the conversion units might be installed at their own sites without regard for coal chemistry, accepting any minor reduction in cash flow that will occur should the chemistry not be optimum.

Second, employment will also play a great role in site and resource selection when individual mines are involved as employment opportunities differ depending on the resource used in the conversion. Employment which derives from the conversion process itself without regard for whether waste or normal production coal is used will be relatively insignificant as the conversion units require minimum operating manpower. Employment from the conversion of mined coal will be substantially greater as it would be a function of coal production as well as coal conversion.

Third, the investment return from gob or culm conversion is higher than the return from the use of production coal. This factor would influence selection of the resource to be converted should the mines elect to limit conversion to either one or the other of these resources rather than conversion of both.

Fourth, there are dramatic environmental advantages, the primary one being the removal of culm mountains. Culm is mine refuse, left after the breaker has knocked out the pure coal. A billion ton eyesore, it litters southwestern Virginia, polluting ground water and ruining real estate.

There is no question that the use of the hydrocarbon catalytic converters would provide a major enconomic boost to the Virginia mines, and fortunately the capital investment per unit is extremely low—$3 million in 1983 dollars. Another option exists, and while it would take considerable coordination and selflessness on the part of certain of the larger mines, consideration might even be given to forming a cooperative of some sort to finance and operate the catalytic conversion units committing a part of its profit stream as an offset against rail costs which are having such a dramatic and, in some instances, such a disastrous impact on the mining community.

There are obviously a great many interesting aspects to the situation which should be examined. Not the least of these would be the involvement of the Federal Government and the Commonwealth of Virginia.

In this respect, should the coal mines elect to request project support from the SFC, VFCA, DOE, and so forth, it is important that conversion site decisions to be taken by the involved mines prior to taking the matter to these agencies be made. This will preempt any site selections by elements of the Federal and State government which could be counter to mine interests.

Further, the hydrocarbon catalytic conversion production elements planned as an integral part of financing coal fired locomotives and coal water mixture fired ships have a dual purpose, to permit product diversification, and of overriding importance, to provide cash flow to reduce, if not eliminate the need for Federal funding for other than locomotive and ship fabrication.

The components of our coal strategy. On January 9 of this year were provided all of the information to your office regarding the hydrocarbon catalytic conversion system for possible use by one or more of the Virginia coal mines.

In our view, the project has three basic segments: project validation, plant, locomotive and ship construction, and plant, locomotive and ship operation, with the latter two being phases III and IV of the project as briefed to the subcommittee in the document we sent to your office.

The first segment, project validation, is composed of three steps. The first of these involved concept formulation, system analysis, program planning and coordination. The second and third steps comprise phases I and II of the project, the preengineering feasibility studies in phase I, and the design engineering and pricing, as well as the formulation of the proposals for submission to the SFC and VFCA being accomplished during phase II.

One of the conclusions of the concept formulation, system analysis and program planning segment was that phase I and II data were interrelated, and thus both phases need be completed for project validation, with funding to permit completion estimated at $6 million. The cost of the respective phases as provided in our briefing document serve only to show that the estimated cost of phase II, involving design and engineering contracts with American National Hydrocarbon, Atlantic Research, and Bechtel would require the bulk of the funds required for project validation.

Whatever the costs of phase I and II may be, we intend that the funds be derived solely from the operating corporation which is to be fully capitalized by the participation shareholders. Involvement of the Federal Government and the VFCA in funding either phase I or II is therefore not anticipated.

Our phased program management approach is that in phase I the preengineering data collection and analysis, and the construction of one hydrocarbon catalytic converter which has the capacity to produce 27,000 barrels of diesel fuel in a month. Assuming that American Synthetic Fuels Corp., is involved in a project support role, it is our considered opinion that neither the locomotive technology nor the Virginia coal water mixture synfuel project need suffer any adverse financial impact from independent participation by interested mines in the hydrocatalytic conversion element of the overall synfuel project. We believe that we can finance the reintroduction of coal as fuel for locomotives by utilizing 20 of these convertors to provide the necessary cash-flow to offset the engineering costs for construction.

The roles that we would fill as the projector integrator derives principally from our extensive work with the SFC and the VFCA and our contract with American Hydrocarbon for the use of this technology.

My closing thoughts—most importantly, to get back to where I started, the entire coal strategy, synthetic diesel fuel, coal fired locomotives, and coal water mixture fired ships, economic and informational, must be integrated. One of our real strengths is our coal and economy. One of our prime objectives is to promote the economic well being of our people. For this reason, our strategy is designed to conduct the aforementioned programs which will create thousands of new jobs and new services with the State through the framework of approved long range plans and clearly defined fiscal envelopes. We cannot seek more.

We have tried to analzye the resulting risks put first things first, and develop plans for how we will conduct our selves if worst comes to worst.

The exercise of the powers granted by the Energy Security Act and the Virginia Fuel Conversion Authority Act in all respects are for the benefit of the inhabitants of the Commonwealth, for the increase of our commerce and for the protection of our safety, health, welfare, convenience, and prosperity. Persistence and constancy of purpose are virtues. Turbulence is an expensive vice. The next 20 years of history is ours to decide. Energy independence is our principal security concern.

Our projections are based upon formula, notably proven items, not paper tigers vulnerable to miscalculation and design flaw.

And I thank you.

[The prepared statement of Mr. Matthews follows:]

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RICHMOND, VIRGINIA 23220

STATEMENT MADE BEFORE SENATOR JOHN W. WARNER
SUBCOMMITTEE ON ENERGY AND MINERAL RESOURCES
"REINTRODUCTION OF COAL AS FUEL FOR RAILROAD LOCOMOTIVES"

DETAILS OF COAL FUEL STRATEGY
FOSTERING THE INFRASTRUCTURE OF ENERGY INDEPENDENCE

BY DARYL A. MATTHEWS, PRESIDENT
AMERICAN SYNTHETIC FUELS CORPORATION

DURING THE NEXT FIVE MONTHS THE UNITED STATES SYNTHETIC FUELS CORPORATION WILL BE SOLICITING PROPOSALS TO ASSIST A PROJECT FOR PRODUCING COAL WATER FUEL FOR USE IN INDUSTRIAL FUEL BURNING FACILITIES. AS A RESULT OF THIS THERE HAS EMERGED THE FRAMEWORK OF A VIRGINIA STRATEGY AND - OF DIRECT INTEREST TO YOU HERE THIS MORNING - A BODY OF ENERGY STRATEGY FOR FINANCING THE CONSTRUCTION OF A PROTOTYPE LOCOMOTIVE.

LAST MONTH THE EXECUTIVE DIRECTOR OF THE VIRGINIA FUEL CONVERSION AUTHORITY SUMMARIZED HIS FUNDAMENTAL COAL STRATEGY OBJECTIVES IN NINE WORDS. "VIRGINIA COAL IS JUST RIGHT FOR COAL WATER MIXTURES." THROUGH THE PROMOTION OF VIRGINIAN PRODUCED COAL WATER MIXTURES ECONOMIES CAN BE SUBSTANTIALLY ACHIEVED TO MITIGATE AND NUETRALIZE ANY NEGATIVE IMPACTS OF INTERRUPTION OF FOREIGN OIL SUPPLIES DURING NATIONAL EMERGENCIES, AND REMOVE OUR NATIONAL RAILROAD SYSTEM FROM DEPENDENCE ON IMPORTS OF OPEC OIL.

COAL WATER MIXTURES WITH SMALL AMOUNTS OF CHEMICAL STABILIZERS ARE PROJECTED TO BE ABOUT 20% LESS EXPENSIVE THAN NO. 6 FUEL OIL ON A BTU BASIS. BOILERS CAPABLE OF BURNING BOTH COAL AND OIL CAN BE INEXPENSIVELY CONVERTED TO FIRE COAL WATER MIXTURES. THE POTENTIAL FOR THIS FUEL IS MEASURED IN THE 100 MILLION TONS OF COAL RANGE.

THIS MORNING I WOULD LIKE TO SPELL OUT FOR YOU, IN AS MUCH DETAIL AS TIME PERMITS, THE BASIS FOR OUR STRATEGY, THE NATURE OF ITS COMPONENTS, AND THE CONCLUSIONS THAT ARE PERTINENT TO THIS SUBCOMMITTEE.

IT IS APPROPRIATE TO DO SO HERE, THIS MORNING, BECAUSE BURNING FUEL DERIVED FROM COAL HAS BEEN ACCORDED A HIGH PRIORITY BY SENATOR WARNER, AND A FIRST PRIORITY WITHIN THAT PROGRAM HAS GONE TO CONVERTING THE NATIONS LOCOMOTIVES TO COAL. BEING FIRST AMONG FIRST PLACES ENORMOUS RESPONSIBILITY ON ALL OF US IN THE COAL CONVERSION BUSINESS. IT IS A RECOGNITION LONG AWAITED, BUT NOW AWARDED IT MUST BE FULLY DISCHARGED.

FOUNDATION OF AMERICAN SYNTHETIC FUELS STRATEGY

NO GOVERNMENT CAN AFFORD AN OVERHAUL OF ITS GRAND STRATEGY EVERY FOUR YEARS. FOREIGN POLICY AND DEFENSE PLANNING MUST BE CONCEIVED AND EXECUTED AROUND CERTAIN BASIC PRINCIPLES AND OBJECTIVES. IN THE CASE OF THE UNITED STATES, WE SEE THESE AS THE ACHIEVEMENT OF ENERGY SECURITY AS ESSENTIAL TO THE HEALTH OF THE NATIONAL ECONOMY, THE WELL-BEING OF OUR CITIZENS AND THE MAINTENANCE OF NATIONAL SECURITY AS EMBODIED IN THE ENERGY SECURITY ACT, AND THE VIRGINIA FUEL CONVERSION AUTHORITY ACT, SECONDLY, IN ORDER TO RESPOND TO ACTIONS OCCURING OUTSIDE OF THE UNITED STATES WHICH COULD RESULT IN THE TERMINATION OR REDUCTION OF THE AVAILABILITY OF STRATEGIC AND CRITICAL MATERIALS, INCLUDING ENERGY AND WHICH WOULD ADVERSELY AFFECT THE NATIONAL DEFENSE PREPAREDNESS OF THE U.S. WHICH IS ESSENTIAL TO NATIONAL SECURITY, IT IS ALSO NECESSARY AND APPROPRIATE TO ASSURE DOMESTIC ENERGY SUPPLIES FOR NATIONAL DEFENSE NEEDS; THIRDLY, TO USE OF THESE ACTS TO HELP PRIVATE ENTERPRISE CONSTRUCT FACILITIES FOR THE PRODUCTION OF SYNTHETIC FUELS, PARTICULARLY FROM COAL.

THESE BASIC PURPOSES, PLUS A DECADE OF EXPERIENCE, PROVIDE THE FOUNDATION FOR THIS CORPORATIONS' COAL STRATEGY.

PLANNING HAS BEEN COMPLETED FOR THE IMPLEMENTATION OF AN INDUSTRIAL PROJECT IN SOUTHWESTERN VIRGINIA WHICH WILL PROVIDE A NEW ANNUAL MARKET FOR APPROXIMATELY TEN MILLION TONS OF VIRGINIA COAL. TO A LARGE SEGMENT OF THE MINING COMMUNITY WHICH SUFFERS FROM AN UNEMPLOYMENT RATE ESTIMATED TO BE OVER 28% RESULTING FROM MASSIVE AND CONTINUING REDUCTIONS IN COAL SALES IN PAST YEARS, PROJECT IMPLEMENTATION WOULD MEAN AT LEAST PARTIAL RECOVERY IN THE IMMEDIATE FUTURE.

RELEVANT TO THE EXISTING VIRGINIA COAL COMMUNITY ECONOMIC PROBLEMS, NEW TECHNOLOGICAL ADVANCES NOW AVAILABLE PERMIT IMMEDIATE CONSTRUCTION AND OPERATION OF RELATIVELY SMALL SYNTHETIC FUEL PRODUCTION FACILITIES AT INDUSTRIAL MINE LOCATIONS. EACH OF THESE FACILITIES WILL PROCESS APPROXIMATELY NINE HUNDRED THOUSAND TONS OF COAL ANNUALLY, CONVERTING THE COAL TO DIESEL FUEL, THAT IS 25% LESS EXPENSIVE THAN PETROLEUM BASED DIESEL FUEL. KEY PLANNING FACTORS GERMANE TO THE CONSTRUCTION AND OPERATION OF THESE UNITS HAVE BEEN PROVIDED TO THE VIRGINIA FUEL CONVERSION AUTHORITY.

WHILE SUCH AN ACTION COULD OSTENSIBLY WEAKEN THE FINANCIAL VIABILITY OF CONVERTING ALL OF THE NATION'S LOCOMOTIVES TO COAL IN THE LONG TERM, NO LEGAL, MORAL OR TECHNICAL REASONS EXIST WHICH WOULD MITIGATE AGAINST THEIR IMMEDIATE INVOLVEMENT. AS A MATTER OF FACT, IN VIEW OF THE CURRENT UNEMPLOYMENT SITUATION IN WESTERN SECTORS OF THE COMMONWEALTH I WOULD THINK THEIR INVOLVEMENT IS ALREADY LONG OVERDUE.

TODAY, THE POLITICS OF OIL, THE LIMITED WORLD SUPPLY, AND THE FACT THAT THE SOVIET ECONOMY IS CONSUMING INCREASING AMOUNTS OF ENERGY AT PROGRESSIVELY HIGHER COST PROVIDE A POTENTIAL SOURCE OF SUPERPOWER CONFRONTATION. TERRORISM, SPACE POLICY, NUCLEAR PROLIFERATION, AND REGIONAL INSTABILITIES ALL ADD UNCERTAINTIES AS WE TRY TO PLAN FOR THE NEXT GENERATION. THESE PLUSES AND MINUSES LEAD US TO SOME CONCLUSIONS IN PLANNING FOR TODAY AND THE FUTURE.

HOW IS IT TO BE DONE

FIRST, EACH OF OUR PLANNED CATALYTIC CONVERSION UNITS ARE TO BE LOCATED AT MINES TO BE SELECTED PRIMARILY UPON (1) THE CHEMISTRY AND THE AMOUNT OF WASTE COAL AVAILABLE FOR CONVERSION AT ONE GROUP OF MINE SITES, (2) THE CHEMISTRY, AMOUNT AND TYPE OF PRODUCTION COAL TO BE CONVERTED AT OTHERS, AND (3) THE GUARANTEED RETURN FROM BOTH. THESE SELECTION CRITERIA, PARTICULARLY (3) ABOVE, ARE BIASED, AND PROPERLY SO, BY THE VIRGINIA COAL WATER MIXTURE PROJECT OBJECTIVES.

WHILE THE SAME SELECTION CRITERIA WOULD APPLY SHOULD INDIVIDUAL MINES BECOME INVOLVED, THEIR PRIORITIES WOULD DIFFER. AS AN EXAMPLE, THE CONVERSION UNITS MIGHT BE INSTALLED AT THEIR OWN SITES WITHOUT REGARD FOR COAL CHEMISTRY, ACCEPTING ANY MINOR REDUCTION IN CASH FLOW THAT WILL OCCUR SHOULD THE CHEMISTRY NOT BE OPTIMUM.

SECOND, EMPLOYMENT, WILL ALSO PLAY A GREATER ROLE IN SITE AND RESOURCE SELECTION WHEN INDIVIDUAL MINES ARE INVOLVED AS EMPLOYMENT OPPORTUNITIES DIFFER DEPENDING ON THE RESOURCE USED IN CONVERSION.

EMPLOYMENT WHICH DERIVES FROM THE CONVERSION PROCESS ITSELF WITHOUT REGARD FOR WHETHER WASTE OR NORMAL PRODUCTION COAL IS USED WILL BE RELATIVELY INSIGNIFICANT AS THE CONVERSION UNITS REQUIRE MINIMUM OPERATING MANPOWER.

EMPLOYMENT FROM THE CONVERSION OF MINED COAL WILL BE SUBSTANTIALLY GREATER AS IT WOULD BE A FUNCTION OF COAL PRODUCTION AS WELL AS COAL CONVERSION.

THIRD, THE INVESTMENT RETURN FROM GOB AND CULM CONVERSION IS HIGHER THAN THE RETURN FROM THE USE OF PRODUCTION COAL. THIS FACTOR WOULD INFLUENCE SELECTION OF THE RESOURCE TO BE CONVERTED SHOULD THE MINES ELECT TO LIMIT CONVERSION TO EITHER ONE OR THE OTHER OF THESE RESOURCES RATHER THAN CONVERSION OF BOTH.

FOURTH, THERE ARE DRAMATIC ENVIRONMENTAL ADVANTAGES- THE PRIMARY ONE BEING THE REMOVAL OF CULM MOUNTAINS. CULM IS MINE REFUSE, LEFT AFTER THE BREAKER HAS KNOCKED OUT THE PURE COAL. A BILLION TON EYESORE, IT LITTERS SOUTHWESTERN VIRGINIA, POLLUTING GROUND WATER AND RUINING REAL ESTATE.

THERE IS NO QUESTION THAT THE USE OF THE HYDROCARBON CATALYTIC CONVERTERS WOULD PROVIDE A MAJOR ECONOMIC BOOST TO THE VIRGINIA MINES, AND FORTUNATELY THE CAPITAL INVESTMENT PER UNIT IS EXTREMELY LOW, ($3 MILLION IN 1983 DOLLARS). ANOTHER OPTION EXISTS, AND WHILE IT WOULD TAKE CONSIDERABLE COORDINATION AND SELFLESSNESS ON THE PART OF CERTAIN OF THE LARGER MINES, CONSIDERATION MIGHT EVEN BE GIVEN TO FORMING A COOPERATIVE OF SOME SORT TO FINANCE AND OPERATE THE CATALYTIC CONVERSION UNITS COMMITTING A PART OF ITS PROFIT STREAM AS AN OFFSET AGAINST RAIL COSTS WHICH ARE HAVING SUCH A DRAMATIC AND IN SOME INSTANCES SUCH A DISASTEROUS IMPACT ON THE MINING COMMUNITY.

THERE ARE OBVIOUSLY A GREAT MANY INTERESTING ASPECTS TO THE SITUATION WHICH SHOULD BE EXAMINED. NOT THE LEAST OF THESE WOULD BE THE INVOLVEMENT OF THE FEDERAL GOVERNMENT AND THE COMMONWEALTH OF VIRGINIA.

IN THIS RESPECT, SHOULD THE COAL MINES ELECT TO REQUEST PROJECT SUPPORT FROM THE SFC, VFCA, DOE, ETC., IT IS IMPORTANT THAT CONVERSION SITE DECISIONS BE TAKEN BY THE INVOLVED MINES PRIOR TO TAKING THE MATTER TO THESE AGENCIES. THIS WILL PREEMPT ANY SITE SELECTIONS BY ELEMENTS OF THE FEDERAL AND STATE GOVERNMENT WHICH COULD BE COUNTER TO MINE INTERESTS.

FURTHER, THE HYDROCARBON CATALYTIC CONVERSION PRODUCTION ELEMENTS PLANNED AS AN INTEGRAL PART OF FINANCING COAL FIRED LOCOMOTIVES AND COAL WATER MIXTURE FIRED SHIPS HAVE A DUAL PURPOSE. I.E., TO PERMIT PRODUCT DIVERSIFICATION, AND OF OVER-RIDING IMPORTANCE, TO PROVIDE CASH-FLOW TO REDUCE IF NOT ELIMINATE THE NEED FOR FEDERAL FUNDING FOR OTHER THAN LOCOMOTIVE AND SHIP FABRICATION.

COMPONENTS OF OUR COAL STRATEGY

ON JANUARY 9, 1984, WE PROVIDED ALL OF THE INFORMATION TO SENATOR WARNER REGARDING THE HYDROCARBON CATALYTIC CONVERSION SYSTEM FOR POSSIBLE USE BY ONE OR MORE OF THE VIRGINIA COAL MINES.

IN OUR VIEW, THE PROJECT HAS THREE BASIC SEGMENTS: PROJECT VALIDATION, PLANT, LOCOMOTIVE AND SHIP CONSTRUCTION, AND PLANT, LOCOMOTIVE AND SHIP OPERATION, WITH THE LATTER TWO BEING PHASES III AND IV OF THE PROJECT AS BRIEFED TO THE SUBCOMMITTE IN THE DOCUMENT.

THE FIRST SEGMENT, PROJECT VALIDATION, IS COMPOSED OF THREE STEPS. THE FIRST OF THESE INVOLVED CONCEPT FORMULATION, SYSTEM ANALYSIS, PROGRAM PLANNING AND COORDINATION. THE SECOND AND THIRD STEPS COMPRISE PHASES I AND II OF THE PROJECT, I.E., PRE-ENGINEERING FEASIBILITY STUDIES IN PHASE I, AND THE DESIGN ENGINEERING AND PRICICING, AS WELL AS THE FORMULATION OF THE PROPOSALS FOR SUBMISSION TO THE SFC AND VFCA BEING ACCOMPLISHED DURING PHASE II.

ONE OF THE CONCLUSIONS OF THE CONCEPT FORMULATION, SYSTEM ANALYSIS AND PROGRAM PLANNING SEGMENT WAS THAT PHASE I AND II DATA WERE INTERRELATED, AND THUS BOTH PHASES NEED BE COMPLETED FOR PROJECT VALIDATION, WITH FUNDING TO PERMIT COMPLETION ESTIMATED AT $6 MILLION. THE COST OF THE RESPECTIVE PHASES AS PROVIDED IN OUR BRIEFING DOCUMENT SERVE ONLY TO SHOW THAT THE ESTIMATED COST OF PHASE II, INVOLVING DESIGN AND ENGINEERING CONTRACTS WITH AMERICAN NATIONAL HYDROCARBON, ATLANTIC RESEARCH AND BECHTEL WOULD REQUIRE THE BULK OF THE FUNDS REQUIRED FOR PROJECT VALIDATION.

WHATEVER THE PHASE I AND II COSTS MAY BE, WE INTEND THAT THE FUNDS BE DERIVED SOLELY FROM THE OPERATING CORPORATION WHICH IS TO BE FULLY CAPITALIZED BY THE PARTICIPATING SHAREHOLDERS. INVOLVEMENT OF THE FEDERAL GOVERNMENT AND THE VFCA IN FUNDING EITHER PHASE I OR II IS THEREFORE NOT ANTICIPATED.

PHASED PROGRAM MANAGEMANT APPROACH

1. PHASE I: PRE-ENGINEERING DATA COLLECTION AND ANALYSIS, AND THE CONSTRUCTION OF ONE HYDROCARBON CATALYTIC CONVERTER.

2. PHASE II: DESIGN, ENGINEERING AND COST ANALYSIS. PROMULGATE AND SUBMIT FORMAL PROPOSAL TO THE SFC AND VFCA FOR COAL WATER MIXTURE PLANT AND THE USE OF 20 HYDROCARBON CATALYTIC CONVERTERS, ONE LOCOMOTIVE AND ONE SHIP.

3. PHASE III: FABRICATION OF THE COAL WATER MIXTURE PLANT, LOCOMOTIVE AND SHIP AND COMPLETION OF THE CONVERSION UNITS.

4. PHASE IV: OPERATION

PROJECT INTEGRATOR

ASSUMING APPROPRIATE AMERICAN SYNTHETIC FUEL CORPORATION INVOLVEMENT IN A PROJECT SUPPORT ROLE, IT IS OUR CONSIDERED OPINION THAT NEITHER THE LOCOMOTIVE TECHNOLOGY NOR THE VIRGINIA COAL WATER MIXTURE SYNFUEL PROJECT NEED SUFFER ANY ADVERSE FINANCIAL IMPACT FROM INDEPENDENT PARTICIPATION BY INTERESTED MINES IN THE HYDROCARBON CATALYTIC CONVERSION ELEMENT OF THE REINTRODUCTION OF COAL AS FUEL FOR RAILROAD LOCOMOTIVES. UNDER THESE CIRCUMSTANCES WE WOULD BE WILLING TO ASSIST THEM IN THE ACQUISITION AND OPERATION OF ONE OR MORE OF THESE CONVERSION FACILITIES.

THE ROLES WE WOULD FILL AS THE PROJECT INTEGRATOR ARE OF GREATER IMPORTANCE THAN MIGHT NORMALLY BE APPRECIATED. FIRST, ABYSMAL AS IT MAY SEEM, A DEFINITIVE KNOWLEDGE OF THE WASHINGTON AND VIRGINIA SYNTHETIC FUEL SCENE AND THE PERSONNEL THAT DRIVE ACTIONS WITHIN THE VARIOUS AGENCIES, AS WELL AS MAINTENANCE OF DAILY LIAISON TO ENABLE THEIR CONTINUING INTRODUCTION OF BIAS, IS OF EQUAL IF NOT GREATER IMPORTANCE TO THE APPROVAL PROCESS THAN IS TECHNICAL AND FINANCIAL CONTENT.

SECOND, THE VALUE OF HAVING THE INDEPENDENT AGENCY RESPONSIBLE FOR CONSOLIDATION AND VALIDATION OF PROJECT DATA FOR THE PARTICIPANTS ALSO RESPONSIBLE FOR CONDUCTING THIS CRITICAL LIAISON FUNCTION CANNOT BE OVERSTRESSED. AS THE PROJECT INTEGRATOR TEAM, WE WILL SATISFY THIS REQUIREMENT.

WE NOT ONLY BRING THESE CAPABILITIES AND CAPACITIES TO THE TABLE, BUT ALSO OUR ENVIABLE POSITION OF BEING KNOWN THROUGHOUT THE VIRGINIA SYNTHETIC FUEL TECHNICAL COMMUNITY AS BEING OBJECTIVE AND WITHOUT A VESTED INTEREST IN THE LOCOMOTIVE ASPECT OF THE PROJECT ITSELF.

IN ADDITION TO INCLUDING THE BASIC ECONOMICS ASSOCIATED WITH THE OPERATION OF ONE OF THESE UNITS, I HAVE ALSO DESCRIBED THE AMERICAN SYNTHETIC FUEL CORPORATION FUNCTION AND THE COST THEREOF IN THE DOCUMENT SO THE SUBCOMMITTE WILL KNOW THE SHORT AND LONG TERM FINANCIAL COMMITMENTS THAT ACCRUE WITH RESPECT TO ASF SHOULD AN AFFIRMATIVE DECISION TO PROCEED BE TAKEN.

ANOTHER ASPECT YOU MAY CARE TO CONSIDER DURING ANY PRELIMINARY DISCUSSIONS YOU MAY HAVE WITH MINE PRINCIPALS DERIVES FROM THE DOMINO EFFECT THAT OPERATION OF ONE CONVERSION FACIILITY WILL UNDOUBTEDLY HAVE THROUGHOUT THE MINING COMMUNITY IN ADDITION TO PROVIDING CASH FLOW FOR THE LOCOMOTIVE. THE PROBABILITY THAT SUCCESSIVE PLANTS WILL BE DESIRED IS QUITE HIGH, THUS FROM A COST EFFECTIVENESS POINT OF VIEW, THIS FACTOR WARRANTS CONSIDERATION EARLY IN THE DECISION CYCLE.

A DEMONSTRATION OF THE EXISTING CONVERSION UNIT CAN BE ARRANGED SHOULD THE MINES BE INTERESTED AND PENDING RECEIPT OF THE SUBCOMMITTEE'S ADVICE ON THE MATTER, I WOULD BE HAPPY TO MEET AND DISCUSS THE MATTER FURTHER WITH THE SUBCOMMITTEE AND MINE PRINCIPALS ON A COST REIMBURSEMENT BASIS.

CONCLUDING THOUGHTS

MOST IMPORTANTLY, TO GET BACK TO WHERE I STARTED, THE ENTIRE COAL STRATEGY - SYNTHETIC DIESEL FUEL, COAL FIRED LOCOMOTIVES AND COAL WATER MIXTURE FIRED SHIPS, ECONOMIC AND INFORMATIONAL - MUST BE INTEGRATED. ONE OF OUR REAL STRENGTHS IS OUR COAL AND ECONOMY. ONE OF OUR PRIME OBJECTIVES IS TO PROMOTE THE ECONMOMIC WELL-BEING OF OUR PEOPLE. FOR THIS REASON OUR STRATEGY IS DESIGNED TO CONDUCT THE AFOREMENTIONED PROGRAMS WHICH WILL CREATE THOUSANDS OF NEW JOBS AND NEW SERVICES WITHIN THE STATE THROUGH THE FRAMEWORK OF APPROVED LONG RANGE PLANS AND CLEARLY DEFINED FISCAL ENVELOPES. WE CANNOT SEEK MORE.

WE HAVE TRIED TO ANALYZE THE RESULTING RISKS PUT FIRST THINGS FIRST, AND DEVELOP PLANS FOR HOW WE WILL CONDUCT OURSELVES IF WORST COMES TO WORST.

THE EXERCISE OF THE POWERS GRANTED BY THE ENERGY SECURITY ACT AND THE VIRGINIA FUEL CONVERSION AUTHORITY ACT IN ALL RESPECTS ARE FOR THE BENEFIT OF THE INHABITANTS OF THE COMMONWEALTH, FOR THE INCREASE OF OUR COMMERCE AND FOR THE PROTECTION OF OUR SAFETY, HEALTH, WELFARE, CONVENIENCE AND PROSPERITY. PERSISTENCE AND CONSTANCY OF PURPOSE ARE VIRTUES. TURBULENCE IS AN EXPENSIVE VICE. THE NEXT 20 YEAR PHASE OF HISTORY IS OURS TO DECIDE. ENERGY INDEPENDENCE IS OUR PRINCIPLE SECURITY CONCERN.

OUR PROJECTIONS ARE BASED UPON FORMULA, NOTABLY PROVEN ITEMS, NOT PAPER TIGERS VULNERABLE TO MISCALCULATION AND DESIGN FLAW.

THANK YOU

CONTACT:

MR. D.A. MATTHEWS
2166 ELKRIDGE LANE
RICHMOND, VIRGINIA 23223

TELEPHONE: (804) 780-0181

Senator **Warner**. Thank you for a very precise and informative contribution to this record.

And now, Mr. Kuntz. Last but not least. We thank you for your patience and having traveled down from New York. Your statement, in its entirety, will be put into the record. Hopefully, you can summarize it. Take what time you feel is required.

STATEMENT OF WILLIAM KUNTZ III, ON BEHALF OF WESTRAIL TRANSPORTATION CO., AND WOLFPACK ELECTRONICS

Mr. **Kuntz**. If I can, I will briefly go through it. I think I will cover the many points that have already been discussed today.

Senator **Warner**. You've obviously done a lot of work in this area and have a grasp on the potential for this concept.

Mr. **Kuntz**. Thank you.

Senator **Warner**. It may take the vitality and the energy of your generation and Mr. Matthews, because my generation—I can't get them moving so far.

Mr. **Kuntz**. To that, Senator, I can fortunately say we have the coal in this country to worry about this problem.

Mr. Chairman, members of the committees, and guests. I would like to thank you for the chance to speak on the topic that is currently being studied.

In 1950, there were 26,860 steam locomotives in service in the United States. By 1965, there were 89. Consumption of coal for fuel in 1950 exceeded 55,000 units of 1,000 short tons. By 1965 this had fallen to 4 units.

In contrast, the need for diesel oil has climbed to over 4,000 million gallons. This does not include fuel for trucks nor other uses. Nor does it include the amount of oil used to generate the thousands of millions of kilowatts of electricity used in propulsion of all electric locomotives used mostly in the Eastern United States.

In 1974, American railroads carried almost 400,000 million tons of coal using next to none for locomotive fuel. Classified as prime movers by the U.S. Department of Commerce, locomotives provide almost 60 million horsepower to move mostly the freight of this Nation.

Yet in this country the use of coal for these engines is almost nonexistent.

Senator **Warner**. Excuse me, you say almost. It is nonexistent, isn't it? Is there a single coal locomotive operating today other than the tourist attractions? And I don't mean to demean it but the very valuable tourist attractions very frequently are operated by—I think one or two Eastern rail systems.

Mr. **Kuntz**. There's another, Scenic Tours Railroads.

Senator **Warner**. I know there's one out in Colorado, the Silverton Line is steam, still. So I guess there are a handful?

Dr. **Davoud**. There's another one, I believe, that runs up to the Homestead.

Senator **Warner**. Thank you. Excuse me for interrupting.

Mr. **Kuntz**. While much of the rest of the world still uses coal fired engines in many diverse applications, there is not one major manufacturer in the country for this type of engine.

It has become apparent over the last few years to most of us that we are quite dependent on oil imports which come from parts of the world where we have only marginal control of supplies. In the event of a real crisis in the obtaining of fuel stocks, railroads are in direct competition with both the auto and truck sectors of our economy.

It would serve us greatly to create these alternate methods of developing motive power from coal. After the Second World War, there was an effort by a number of our industrial leaders to develop coal/gas turbines for use in the railroad industry. Due to the general adoption of diesel locomotives by the major railroads, these efforts were in the nature of demonstration and development projects which never reached full scale production.

What I seek, and I am sure it is shared by many here, is the industrial rehabilitation of the old concept into a new and economically viable product that will not only serve in this country but be available for export in such numbers as to provide competition for existing fleets of diesels in service now. The sale of 100 units a year at the price of $10 million each would reduce our balance of trade by over $1 billion.

If such engines were developed with sufficient power, dependability and economy to be purchased in large numbers by American railroads the drop in the use of oil fuels would be dramatic. Further in times of limited fuel availability, transportation by rail of important cargo would not be imperiled by the allocation of oil fuels where the need might be greater such as for aircraft. Indeed, the development of an engine that would be fueled by coal would go a long way to make this age free of the "oil weapon" that we hear so much about in our foreign relations.

The United States has been historically quite receptive to improvements in the use of steam.

ROBERT FULTON

During the years 1803-07, Fulton brought to a complete success, both mechanically and financially, the system of steam navigation, which fixed his name for all time as one of the world's greatest mechanics.

Further, and this is a magazine article:

A most gratifying experiment was made yesterday afternoon on the Philadelphia, Germantown, and Norristown Railroad. The beautiful locomotive engine and tender, built by Mr. Baldwin, of this city, whose reputation as an ingenious machinist is well known, were for the first time placed upon the road. The engine traveled about 6 miles, working with perfect accuracy and ease in all its parts, and with great velocity.

Hence it is nothing new or novel to draw upon the past to provide for the future.

THE STREAM TURBINE

Steam turbines have almost completely displaced reciprocating engines in large central power stations. Most of the recent developments in steam engineering have been in improvements in steam turbines. . . . Steam turbines operate in a relatively simple way. They will run for several weeks continuously. For the same horsepower a turbine occupies less space and in large size costs less than a reciprocating engine. The turbine has no parts with large masses which move to and fro and cause considerable vibration as they are starting and stopping. The turbine requires no flywheel and can run at very high speeds, 70,000 revolutions per minute having

> been obtained in some cases. A large turbine when run at high speed and when well loaded is more efficient than a reciprocating engine.

I have included in my presentation from the 15th edition of the "Locomotive Cyclopedia" reproductions of some very useful and informative plans contained in Section 11 titled "Turbine Locomotives."

I would specifically like to draw your attention to the last page which shows a rather large locomotive that was built and was experimental. The weight question has come up and this particular engine weighed almost 1,200,000 pounds. So the considerations of weight on the current rail structure is a very——

Senator WARNER. What year was that built?

Mr. KUNTZ. I think this was tested in 1954.

Senator WARNER. Yes. We've got testimony about this locomotive. I recognize it. N&W probably fought the cause of steam right to the end.

Mr. KUNTZ. This section illustrates some of the efforts by both railroads and manufacturers to develop these engines. It also notes that most all efforts were abandoned for such reasons as only diligent research would uncover.

Some period of time has passed since these efforts were curtailed and there have been many advancements in what might be called state of the art. Advances in small power plants as now commonly seen in helicopters, development of flexible conduits as seen in figure 2, and other improvements make possible now construction of engines that were not possible years ago.

> In 1911, Kamerlingh Onmes discovered that the metal lead totally lost its resistance to the passage of electricity below 7°K. Such a second order phase transition into the Superconducting state. . . has subsequently been found in an enormous variety of conductors: metals, alloys, impure semiconductors and semimetals.

It is such progress that now makes the renewal effort possbile in the development of such engines.

I have spent some time considering what course a successful effort might take in developing a new engine. It seemed that a blend of talents and locations would produce the most viable results.

> Pressure vessels constitute a rather specialized but economically important, segment of engineering technology. Traditionally, pressure vessels and pipings have been designed, in large part, on the basis of years of accumulated experience; such experience including, in the early days of steam boilers, several catastrophic failures. As technological developments led to the use of larger vessels and piping along with higher pressures and higher temperatures, empirical methods have gradually been supplanted by analytical techniques.
>
> The advent of nuclear power production, with its unprecedented reliability requirements, has accelerated that trend to the point where it may be stated that design of pressure vessels and piping taxes to the fullest the most advanced tools available in the fields of structural mechanics and material technology.

In Montgomery County, OH, is the city of Dayton. Home of the Wright Brothers, coinventors of the powered airplane, Dayton has become a notable center for research and development with over 11,000 engineers in the area, Wright-Patterson Air Force Base, home of the Air Force Institute of Technology among the other institutions and educational facilities lies directly east of the city.

There are over 981 plants that produce among others, precision parts sold worldwide. In 1983, I purchased a former General Electric concrete warehouse containing 55,000 square feet of unrenovated space. Given the vast pool of talent that exists in the county, this building could be available for a technical center for the development of new and innovative directions in technology.

In Essex County, NY, is Port Henry on Lake Champlain. Site of mining operations from before the time of the American Revolution (figure 1 and figure 3), there still may be available from the Republic Steel Corp. a site for the assembly and testing of prototypes. As there is a high-speed track maintained along the Hudson between Albany and New York City, it would not be necessary to build an expensive test track as is often proposed. Further, the turbine division of General Electric is located at not too great a distance in Schenectady, NY.

I will leave the last paragraph for people's reading rather than reading aloud at this time. I want to thank you for this opportunity to appear.

[The prepared statement of Mr. Kuntz follows:]

S. T. E. M.

LOCOMOTIVE

STEAM TURBINE ELECTROMOTIVE

WILLIAM KUNTZ III
Box 461, Lake Placid, N.Y.
12946-0461

on behalf of

WESTRAIL TRANSPORTATION COMPANY
Essex County, New York

and

WOLFPACK ELECTRONICS
Montgomery County, Ohio

for

UNITED STATES SENATE COMMITTEE ON ENERGY AND NATURAL RESOURCES
The Subcommittee of Energy and Mineral Resources

January 19, 1984

Richmond, Virginia

S. T. E. M.

STEAM TURBINE ELECTRO MOTIVE

MR. CHAIRMAN, MEMBERS OF THE COMMITTEE AND GUESTS; I WOULD LIKE TO THANK YOU FOR THIS CHANCE TO SPEAK ON THE TOPIC THAT IS CURRENTLY BEING STUDIED.

In 1950, there were 26,680 Steam Locomotives in Service in the United States. By 1965, there were 89.(1) Consumption of Coal for fuel in 1950 exceeded 55,452 units of 1,000 short tons. By 1965 this had fallen to 4 units.(2)

In contrast, the need for Diesel Oil has climbed to over Four Thousand Million gallons [4,199,000,000].(3) This does not include fuel for trucks nor other uses. Nor does it include the amount of Oil used to generate the thousand of millions of kilowatts of electricity used in proplusion of all electric locomotives used mostly in the Eastern United States.

In 1974, American Railroads carried almost Four Hundred Thousand Million tons of Coal using next to none for LOCOMOTIVE FUEL.(4)

Classified as Prime Movers by the United States Department of Commerce, Locomotives provide almost Sixty Million Horsepower to move mostly the freight of this nation.(5)

Yet in this country the use of coal for these engines is almost non-existant. While much of the rest of the world still uses coal fired engines in many diverse applications, there is not one major manufacturer in the country for this type of engine.

It has become apparent over the last few years to most of us that we are quite dependent on Oil Imports which come from parts of the world where we have only marginal control of supplies. In the event of a real crises in the obtaining of fuel stocks, Railroads are in direct competition with both the Auto and Truck Sectors of our Economy.

It would serve us greatly to create these alternate Methods of developing motive power from Coal. After the Second World War, there was an effort by a number of our industrail leaders to develop Coal/Gas Turbines for use in the RAILROAD INDUSTRY. Due to the general adoption of Diesel Locomotives by the major Railroads these efforts were in the nature of demonstration and development projects which never reached full scale production.

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STEAM TURBINE ELECTRO MOTIVE

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If such engines were developed with sufficent power, dependability and economy to be pruchased in large numbers by American Railroads the drop in the use of Oil Fuels would be dramatic. Further in times of limited fuel availability, transportation by rail of important cargo would not be imperiled by the allocation of Oil Fuels where the need might be greater such as for aircraft. Indeed, the development of an engine that would be fueled by coal would go a long way to make this age free of the "oil weapon" that we hear so much about in our foreign relations.

The United states has been historically been quite receptive to improvements in the use of steam.

> ROBERT FULTON" During the years 1803-1807, Fulton brought to a complete success, both mechancially and financially, the system of Steam Navigation, which fixed his name for all time as one of the world's greatest mechanics."(6)

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STEAM TURBINE ELECTRO MOTIVE

> "THE STEAM TURBINE. Steam turbines have almost completely displaced reciprocating engines in large central power stations. Most of the recent developments in steam engineering have been in improvements in steam turbines...Steam turbines operate in a relatively simple way. They willrun for several weeks continuously. For the same horsepower a turbine occupies less space and in large size costs less than a reciprocating engine. The Turbine has no parts with large masses which move to and fro and cause considerable vibration as they are starting and stopping. The turbine requires no flywheel and can run at very high speeds, 70,000 revolutions per minute having been obtained in some cases. A large turbine when run at high speed and when well loaded is more effecient that a reciprocating engine."(8)

I have included in my presentation from the 15th(1956) Edition of the LOCOMOTIVE CYCLOPEDIA reproductions of some very usefull and informative plans contained in Section 11 titled TURBINE LOCOMOTIVES.

This section illustrates some of the efforts by both Railroads and Manufacturers to develop these engines. It also notes thatmost all efforts were abandoned for such reasons as only diligent research would uncover.

Some period of time has passed since these efforts were curtailed and there have been many advancements in what might be called state-of-the-art. Advances in small powerplants as now commonly seen in helicopters, development of flexible conduits [FIG 2] and other improvements make possible now construction of engines that were not possible years ago.

> "In 1911, Kamerlingh Onmes discovered that the metal lead totally lost its resistance to the passage of electricity below 7°K. Such a second order phase transition into the SUPERCONDUCTING State... has subsequently been found in an enormous variety of conductors: metals, alloys, impure semi--conductors and semimetals."(9)

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STEAM TURBINE ELECTRO MOTIVE

In ESSEX COUNTY, NEW YORK is Port Henry on Lake Champlain. Site of mining operations from before the time of the American Revolution [FIG 1, FIG 3], there still may be available from the Republic Steel Corporation a site for the assembly and testing of prototypes. As there is high-speed track maintained along the Hudson between Albany and New York City, it would not be necessary to build an expensive "TEST TRACK" as is often proposed. Further the turbine division of GENERAL ELECTRIC is located at not too great a distance in Schenectady,N.Y..

As some present may be aware, there was a total failure in the recent past in Ohio to pass a bond issue to construct a state-wide high-speed passenger rail system. I did attend some of the meetings and read a considerable amount of data for this system. Basically it was an outright purchase of foreign manufactured and developed equipment on the most massive scale. Stringing miles and miles of wires to "new" power plants to power the system. Among other problems overlooked by this project were acid rain, importation of equiptment into the country, high costs in maintaining such a massive investment and so forth. The rather apparent advantages of the development and construction of S.T.E.M. Engines was overwhelmed by the slick presentations of foreign competition. I might also add that foreign presentations were also well-heeled with expense paid trips, etc. I am somewhat pleased to report that after the failure of the bond issue, this part of the State of Ohio's entrenched bureaucracy was abolished and the remainder merged into the Department of Transportation of Ohio.

I again wouldlike to thank you for this opportunity to be heard on this subject.

S. T. E. M.

STEAM TURBINE ELECTRO MOTIVE

FOOTNOTES

1. UNITED STATES DEPARTMENT OF COMMERCE STATISTICAL ABSTRACT (1977) TABLE 1088,1089
2. UNITED STATES DEPARTMENT OF COMMERCE STATISTICAL ABSTRACT (1977) TABLE 1088,1089
3. UNITED STATES DEPARTMENT OF COMMERCE STATISTICAL ABSTRACT (1977) TABLE 1088,1089
4. UNITED STATES DEPARTMENT OF COMMERCE STATISTICAL ABSTRACT (1977) TABLE 1092
5. UNITED STATES DEPARTMENT OF COMMERCE STATISTICAL ABSTRACT (1977) TABLE 975
6. p 388 New Catechism of the STEAM ENGINE. N HAWKINS1900
7. Remarks - THE UNITED STATES GAZETTE, November 24,1832
8. p 253,255 Fundalmentals of machines, Burton L. Cushing 1943
9. p 448 American Scientist, December,1966 Morrel H Cohen
10. p 450a Book review American Scientist, Winter 1968 [Pressure Vessel Design & Analysis by M.B. BICKELL & C RUIZ] 1967

S. T. E. M.

STEAM TURBINE ELECTRO MOTIVE

WESTRAIL TRANSPORTATION COMPANY

Incorporated in Delaware as One Westminister Co,Inc. Westrail is the continuation of efforts in Essex County, New York to move from ill-fated cab company during the 1980 Winter Olympics in Lake Placid, New York into the area of Rail Operations, Research and Development.

In early 1983, the company was forced to seek the protection of Chapter 11 of the Bankruptcy Act by an unnamed National Bank trying to collect over 70% interest on a loan which ultimately resulted in the unnamed Bank being cited for Contempt of Federal Court.

Mr. Peter J. Walsh, Esq. of Wilmington, Delaware is the Current Trustee. [WESTRAIL-Box 461-Lake Placid, N.Y. 12946]

WOLFPACK ELECTRONICS

The principle business of Wolfpack Electronics is the marketing and sale of Radar Detectors currently the "HAWK", "EAGLE" and "GOLDEN EAGLE" Brands. As a participant in a field where there are numerous technical developments there is much in the way of improvements that could be made to our speed and crossing controls.[Wolfpack Electronics Drawer B, Dayton, Ohio 45402 & 221 Crane Street. Dayton,Ohio 45403 1-513-224-3591 & 1-800-824-7888 Opr. 394]

WILLIAM KUNTZ III

Born in 1948 in Dayton, Ohio. Mr. Kuntz has a interest in Westrail and is the principle of Wolfpack Electronics, among his other pursuits . Holding a degree in Business Administration in addition to studies in the fields of Law and Engineering, he has been outspoken in support of THE RAILROAD BUSINESS.

S. T. E. M.

STEAM TURBINE ELECTRO MOTIVE

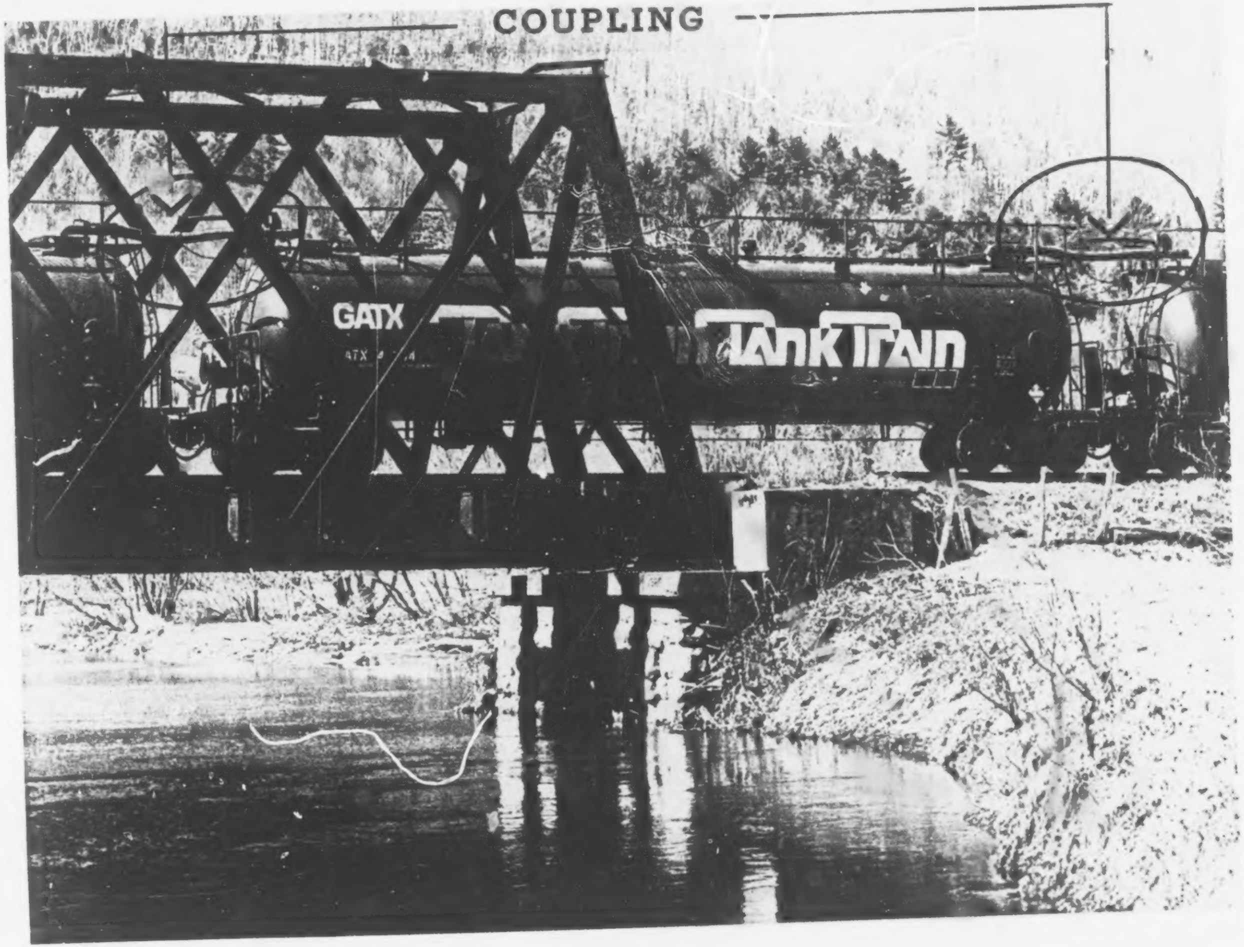
SPECIAL THANKS

TO WAREN DAUBSON
PORT HENRY, NY
PHOTO FIGURES
1, 2 & 3

TO MRS. JOHN C RILL, JR.
MONTGOMERY COUNTY, OHIO
LOCOMOTIVE CYCLOPEDIA

TO THE REAL ESTATE DEPARTMENT OF REPUBLIC STEEL
CLEVELAND, OHIO
&
THE ESSEX COUNTY INDUSTRIAL
DEVELOPMENT AUTHORITY
ELIZABETHTOWN, NEW YORK

NEW HOPE &
IVYLAND RR
NHIR
2051
MCHUGH
BROS
LINE


COUPLING
GATX
TANK TRAIN

Section 11

Turbine Locomotives

THE FIRST SERIOUS DISCUSSION of the gas turbine as a prime mover for American railway motive power was in a report presented before the Railway Fuel and Traveling Engineers' Association in 1939 by a committee of which the late L. P. Michael, mechanical engineer of the Chicago & North Western, was chairman. The reports of this committee were presented over a period of several years.[1]

The basic gas-turbine cycle is the Joule, consisting of adiabatic compression, constant-pressure heating and adiabatic expansion. The large quantities of excess air required to maintain reasonably low maximum temperatures result in a low ratio of positive work done by the turbine to the negative work done by the compressor. A high compression ratio causes a high temperature at the compressor discharge, which limits the energy released by the fuel to a small amount in order not to exceed the permissible turbine entrance temperature. Thus, with a turbine entrance temperature of 1,500 F, an increase in the compression ratio from 2 to 4 with turbine and compressor efficiencies of 80 per cent each reduces the overall ideal shaft efficiency from 51.1 to 42.3 per cent.

The large volumes of air which pass through the gas turbine also magnify the effect of ambient temperature and barometric pressure changes. In a paper before the National Diesel Engine Meeting of the Society of Automotive Engineers in 1953 P. A. McGee presented a rating table for the 4,500-hp gas-turbine locomotives of the Union Pacific which was based on a loss of 300 hp for each 10 deg. increase in ambient temperature and a loss of 100 hp for each 1,000 ft increase in altitude.

The first actual applications of turbines to locomotive use in America were steam. The General Electric Company's locomotive was a turbine-electric drive and included a condenser. The Westinghouse Electric Company developed a steam turbine with gear transmission which was applied to an otherwise essentially conventional Pennsylvania steam locomotive, built by Baldwin Locomotive Works, and a steam-turbine power plant with electric transmission for two Chesapeake & Ohio locomotives, also built by Baldwin. These locomotives operated non-condensing. The problem of providing adequate condenser capacity within locomotive space limitations is difficult of solution; without the condenser, or higher boiler pressures than have been available on reciprocating steam locomotives, the steam turbine offers no appreciable advantage in fuel economy over the reciprocating steam engine.

"John Henry" on the Norfolk & Western

The only steam-turbine locomotive in existence in America today is "John Henry" on the Norfolk & Western. This is a steam-turbine-electric locomotive, the water-tube boiler of which was designed and furnished by The Babcock & Wilcox Company and the steam turbine and electrical equipment by the Westinghouse Electric Corporation. The locomotive was built by the Baldwin-Lima-Hamilton Corporation and went into service on the Norfolk & Western during the summer of 1954.[2] Principal dimensions and weights will be found on Page 444. Its water-tube boiler has a working pressure of 600 psi. It has a starting tractive force of 175,000 lb and a continuous rating of 144,000 lb at 9 mph.

Tested[3] in freight service during 1955 in the mountain-grade territory, Roanoke, Va., to Bluefield, W. Va., it handled 3,673 gross tons, westbound, and 11,620, eastbound, as compared with 3,183 gross tons, westbound, and 10,255, eastbound, handled by a Y6b[4] locomotive. Its average speed was 20.3 mph, eastbound. On a running-time basis it produced 74,400 gross ton miles per train hour, westbound, and 237,900, eastbound, while the Y6b produced 70,000, westbound and 238,100, eastbound. It burned 14.73 tons of coal on the trip, westbound, and 10.89, eastbound, while the consumption of the Y6b was 18.93 tons, westbound, and 12.55, eastbound. Fuel costs per thousand gross ton miles were 24.28 cents and 36.00 cents, respectively, westbound, and 5.83 and 7.54 cents, respectively, eastbound.

In similar tests in comparatively level territory, Williamson, W. Va., to Portsmouth, Ohio, the performance of "John Henry" compared with that of a Class A[5] locomotive was 16,422 tons against 16,028, westbound, and 4,309 against 4,130, eastbound; 27.4 mph average speed against 31.6, westbound, and 32.0 against 36.3, eastbound; 449,700 gross ton miles per train hour on the running-time basis against 506,000, westbound, and 137,800 against 149,900, eastbound; 13.29 tons of coal against 18.4, westbound, and 11.3 against 15.1, eastbound. Fuel costs were 4.31 cents per thousand gross ton miles for the turbine locomotive against 6.12 cents, westbound, and 13.36 against 19.06, eastbound.

GE Oil-Fired Gas-Turbine Locomotive

Of the five gas-turbine locomotive designs which have been proposed in America, so far, only one has actually been placed in service. This is the General Electric 4,500-hp single-unit gas-turbine-electric locomotive the prototype of which was a joint project of the American Locomotive Company and the General Electric Company.[6] It was ready for service late in 1948. In July 1949 it went to the Union Pacific and was assigned to freight service. By the end of 1950 the Union Pacific had ordered 10 units of the same basic design as the prototype,[7] and in 1952 ordered 15 additional units with only minor changes in design. These locomotives were all of 4,500 hp capacity.

These oil-fired locomotives operate, except for starting, on Bunker M oil. This is a Bunker C oil which has been washed and strained to remove soda ash and is marketed by the refiners under the new designation.

In November 1955 the Union Pacific placed an order with the General Electric Company for 15 gas-turbine-electric units which are to develop 8,500 hp and has declared its intention to order later two additional lots of 15 of these locomotives each.[8] An illustration and data pertaining to the design of these locomotives will be found on pgae 437.

The Coal-Burning Gas-Turbine Project

In 1945 a group of eastern railroads originating heavy tonnages of bituminous coal traffic and several large bituminous coal producers established the Locomotive Development Committee within the structure of Bituminous Coal Research, Inc. The objective of the committee was to develop a locomotive which would burn coal more efficiently than the conventional reciprocating steam locomotives then handling most of the traffic of the railroads. Today, reciprocating steam locomotives have been largely replaced by diesel-electric locomotives of several times their thermal efficiency. But with the cost of diesel fuel per million Btu more than four times that of coal on roads originating bituminous coal traffic, the project is still economically attractive.

Since 1945 some $4.5 million have been spent on an extended program of research[9] to find solutions to these problems:

1. Crushing coal to suitable fineness on the locomotive, pressurizing it and feeding it to the combustion chamber under instant control at rates ranging from 500 to 5,000 lb per hour.

2. Burning coal with a combustion efficiency of 90 per cent with outlet temperatures ranging from 700 to 1,300 deg. F.

3. Prevention of trouble caused by the ash content of the coal.

The original conception was to supply the locomotive with any type of coal with any state of dryness. The coal was to be crushed to the requisite fineness and dried on the locomotive. This has been abandoned. The locomotive will be furnished —$^3/_{16}$-in. fines, dried at the mines, shipped in covered hopper cars, stored, and handled on the locomotive by compressed air and the aerator system which fluidizes the entire coal bed. This eliminates the necessity of drying coal on the locomotive and brings the amount of crushing which must be done on the locomotive down to the capacity of a small pulverizer.

The program of tests of the coal handling equipment, the complete combustion system and the turbine which has been under way at the Dunkirk, N. Y., laboratory of the Locomotive Development Committee is to be completed before the end of 1956. Actual building of the locomotive is expected to be under way in 1957.

Illustrations showing the proposed arrangement of components on the locomotive will be found on Pages 442 and 443.

Abandoned Projects

The three other gas-turbine locomotive designs which were proposed and to some extent developed before abandonment were the Westinghouse oil-fired gas-turbine-electric locomotive, the Atchison, Topeka & Santa Fe oil-fired gas-turbine-electric locomotive and the Lima-Hamilton free-piston gas-turbine locomotive.

The Westinghouse locomotive was built and equipped as a laboratory rather than as a commercial locomotive. It was withdrawn from service and dismantled early in 1954.

Neither the Santa Fe locomotive, which was to have been a 3,750-hp single-cab unit, nor the Lima-Hamilton free-piston locomotive advanced beyond the drawing-room stage of their development.

Bibliography

[1] Reports of the Turbine and Condensing Locomotive Committee, Railway fuel and Traveling Engineers' Association for 1939-44 inclusive. See Railway Mechanical Engineer, April, 1940, page 144; November, 1940, page 503; October, 1941, page 420; November, 1942, page 491; December, 1943, page 581; November, 1944, page 524.

[2] Turbine Locomotive Shipped to N & W, Railway Age, May 31, 1954, page 9. Norfolk & Western Receives Experimental Locomotive, Railway Locomotives and Cars, July 1954, page 12.

[3] Promising Results in N & W Turbine Locomotive Tests, Railway Age, January 17, 1955, page 19. Norfolk & Western Tests Turbine Locomotive, Railway Locomotives and Cars, January, 1955, page 56.

[4] The Norfolk & Western Class Y6b is a 2-8-8-2 compound articulated locomotive which develops 126,838 lb tractive force, compound, has 548,500 lb on drivers and carries 300 psi boiler pressure. At speeds above 12 mph its drawbar pull is higher than that of the turbine locomotive.

[5] The Norfolk & Western Class A is a 2-6-6-4 single-expansion articulated locomotive. Its tractive force is 114,000 lb; it carries 432,350 lb on drivers and its boiler pressure is 300 psi. At speed above 13.5 mph the drawbar pull is higher than that of the turbine locomotive.

[6] Alco-GE Gas-Turbine-Electric Locomotive, by P. T. Egbert and G. W. Wilson, Railway Age, July 2, 1949, page 5; Railway Mechanical Engineer, July 1949, page 363.

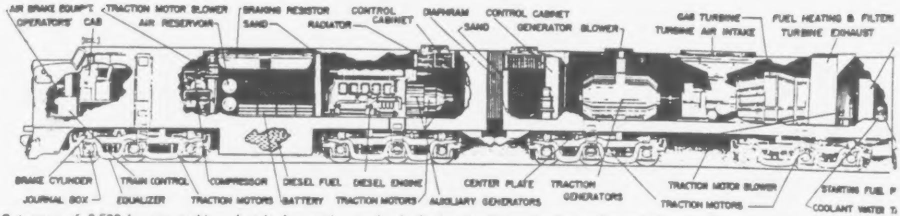
[7] For the performance of this locomotive see the following articles: Report of the Committee on Locomotive Construction, Mechanical Division, Association of American Railroads, Circular No. DV-1217, Exhibit GT-1, page 31. For abstracts, see Railway Age, July 8, 1950, page 54; Railway Mechanical and Electrical Engineer, August, 1950, page 429. Gas-Turbine-Electric Locomotives, by R. A. Williamson (abstract of a paper before the Railway Fuel and Traveling Engineers' Association, 1950), Railway Mechanical and Electrical Engineer, November, 1950, page 673.

[8] For a description of this design see Railway Locomotives and Cars, January, 1956, page 47.

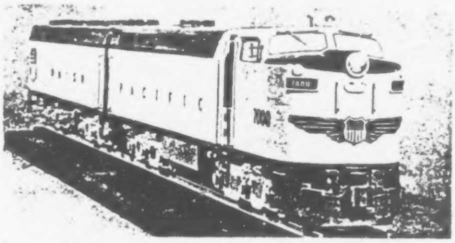
[9] For accounts of the progress of this project see the following articles: The Coal-Fired Gas-Turbine Locomotive, by John I. Yellott and Charles F. Kottcamp, Railway Age, October 5, 1946, page 551. Coal-Burning Gas-Turbine Locomotive, by John I. Yellott, Peter Broadley and Charles F. Kottcamp, Railway Age, January 31, 1948, page 254. Coal-Burning Gas-Turbine Locomotive, by C. K. Steins, Railway Age, November 27, 1948, page 1020. The Gas Turbine at Dunkirk, by John I. Yellott (abstract of a paper presented before the 1950 Midwest Power Conference), Railway Age, April 15, 1950, page 745. Coal-Burning Gas Turbine Moves Ahead, by John I. Yellott, Peter Broadley and Frederick D. Buckley, Railway Age, June 18, 1951, page 39. 1952 a Year of Coal-Burning Turbine Progress, Railway Age, April 20, 1953, page 86. Ash Separation the Key to Coal-Burning Turbine Progress, Railway Age, April 19, 1954, page 44. By 1957 A New Type Locomotive Because Gas Turbines Can Burn Coal, Railway Age, March 5, 1956, page 36.

General Electric 4,500-hp gas-turbine electric in heavy freight service on the Union Pacific at Green River, Wyoming.

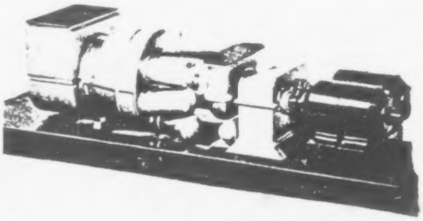
TURBINE LOCOMOTIVES: Gas



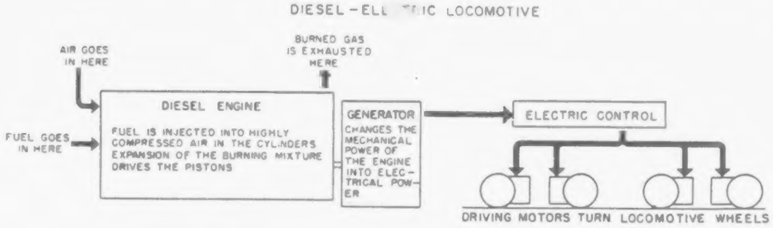
Cut-away of 8,500-hp gas turbine-electric locomotive to be built for the Union Pacific by General Electric. The two units are coupled per nently, the front unit housing the accessory equipment, the back unit the main turbine powerplant and generators. During operation an ir lated 24,000 gallon fuel tender will be coupled behind the locomotive.

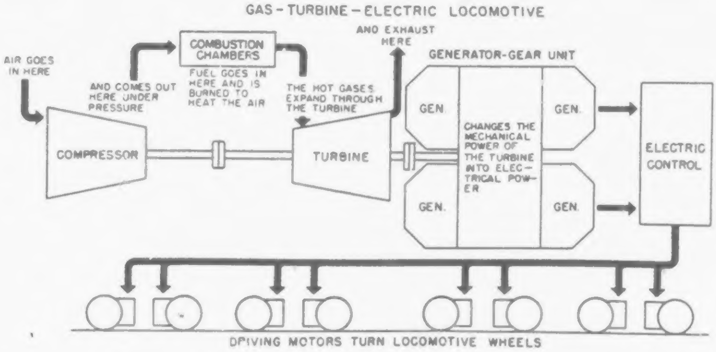


Scale model of above freight locomotive which will have a top speed of 65 mph and will weigh 408 tons.



The powerplant will consist of the turbine (left), connected th reduction gears to electric generators (right) which supply p to the driving motors on the axles.

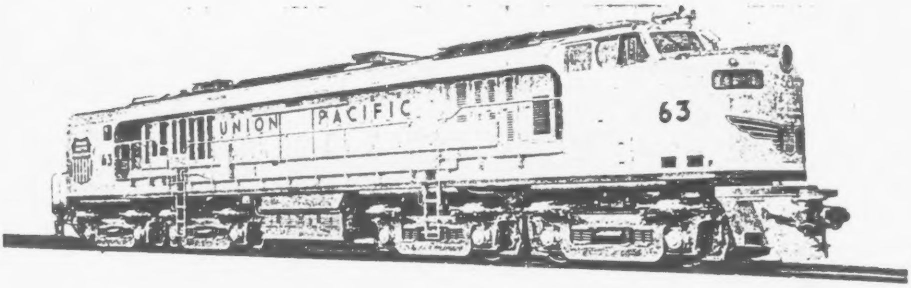

DIESEL-ELECTRIC LOCOMOTIVE
AIR GOES IN HERE
BURNED GAS IS EXHAUSTED HERE
FUEL GOES IN HERE
DIESEL ENGINE
FUEL IS INJECTED INTO HIGHLY COMPRESSED AIR IN THE CYLINDERS EXPANSION OF THE BURNING MIXTURE DRIVES THE PISTONS
GENERATOR
CHANGES THE MECHANICAL POWER OF THE ENGINE INTO ELECTRICAL POWER
ELECTRIC CONTROL
DRIVING MOTORS TURN LOCOMOTIVE WHEELS


GAS-TURBINE-ELECTRIC LOCOMOTIVE
AIR GOES IN HERE
AND COMES OUT HERE UNDER PRESSURE
COMBUSTION CHAMBERS
FUEL GOES IN HERE AND IS BURNED TO HEAT THE AIR
THE HOT GASES EXPAND THROUGH THE TURBINE
AND EXHAUST HERE
GENERATOR-GEAR UNIT
COMPRESSOR
TURBINE
GEN.
GEN.
GEN.
GEN.
CHANGES THE MECHANICAL POWER OF THE TURBINE INTO ELECTRICAL POWER
ELECTRIC CONTROL
DRIVING MOTORS TURN LOCOMOTIVE WHEELS

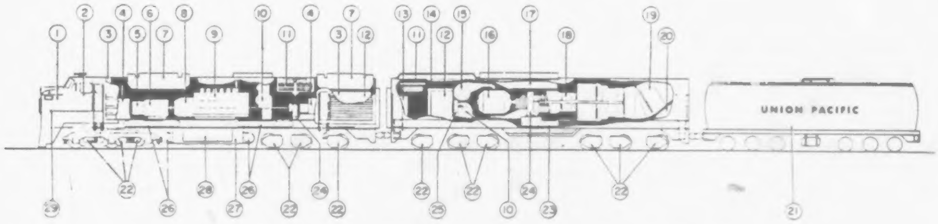
Comparison of diesel-electric and gas turbine-electric locomotive powerplants.

General Electric Company

TURBINE LOCOMOTIVES: Gas

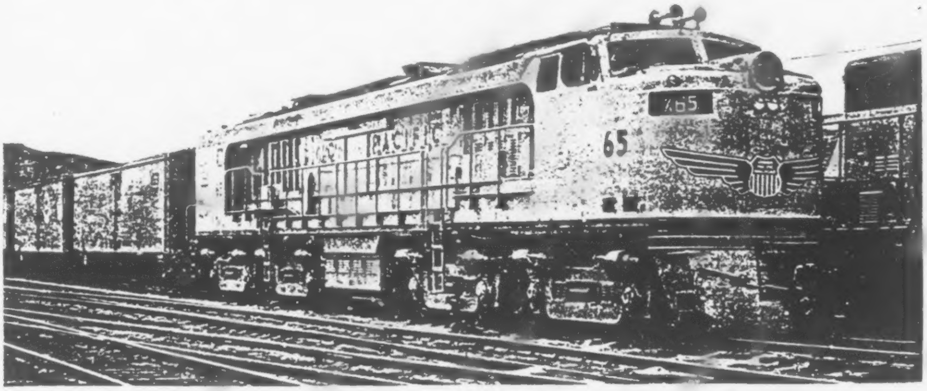


General Electric 4500-hp gas turbine-electric locomotive in service on the Union Pacific.



Location of Parts—General Electric 4,500-hp gas turbine-electric locomotive.

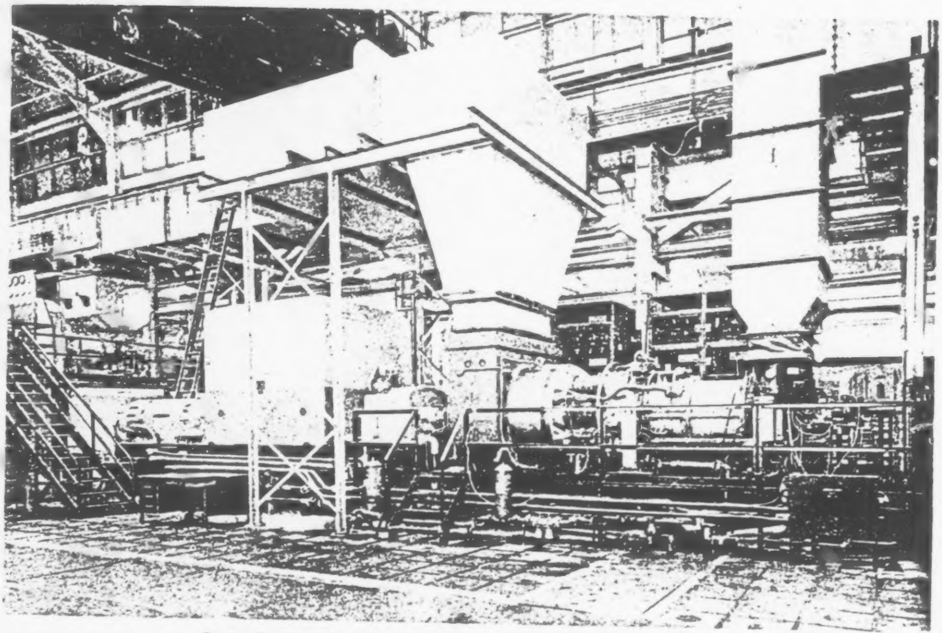
1. Air-Brake Equipment
2. Operator's Cab
3. Auxiliary Control
4. Compressor
5. D-c Auxiliary Generator
6. A-c Generator
7. Braking Resistor
8. D-c Generator
9. Auxiliary Diesel Engine
10. Traction-motor Blower
11. Radiator
12. Propulsion Control
13. Sandbox
14. Excitation Control
15. Generator Blower
16. Traction Generators
17. Turbine Air Intake
18. Gas Turbine
19. Turbine Exhaust
20. Power-plant Equipment
21. Gas-turbine Fuel Tender (furnished by Union Pacific)
22. Traction Motors
23. Lubricating-oil Tank
24. Gear Box
25. Power Transformer
26. Air Reservoirs
27. Diesel Fuel Tank
28. Battery Box
29. Train Control



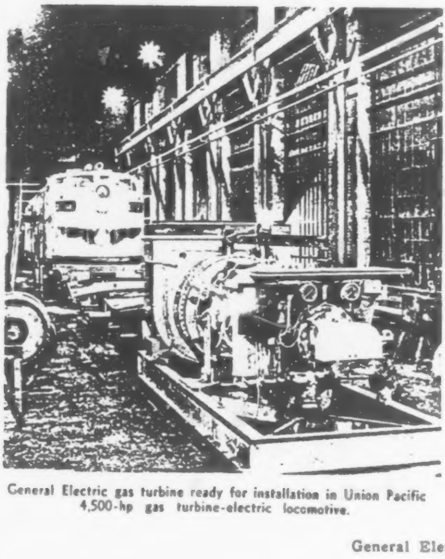
The gas-turbine locomotive in freight service.

General Electric Company

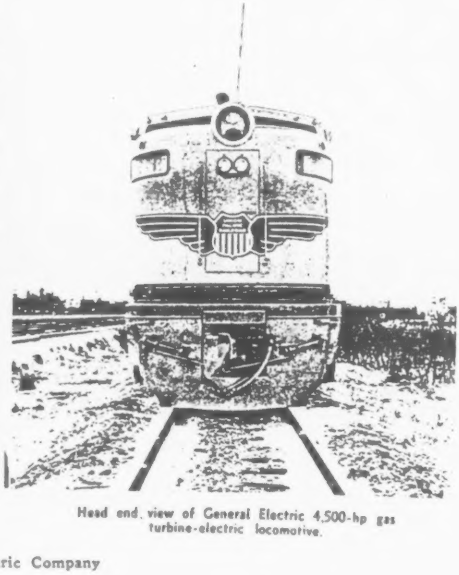
TURBINE LOCOMOTIVES: Gas



General Electric production model gas turbine locomotive power plant on test stand.



General Electric gas turbine ready for installation in Union Pacific 4,500-hp gas turbine-electric locomotive.

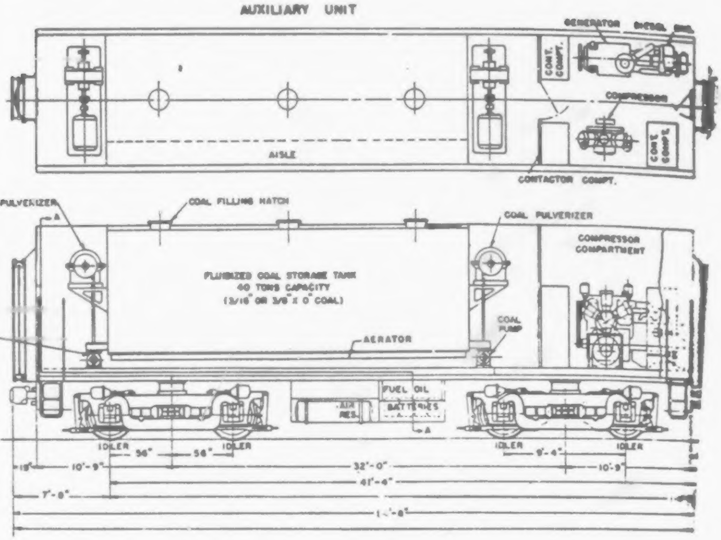


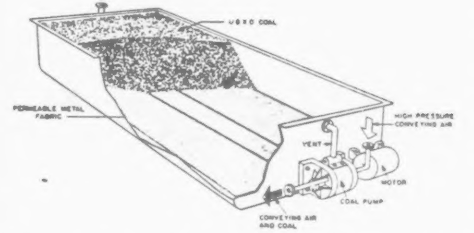
Head end view of General Electric 4,500-hp gas turbine-electric locomotive.

General Electric Company

TURBINE LOCOMOTIVES: Coal

Present Locomotive Development Committee gas turbine could be installed on a six-motored A-unit with fuel handled on a C-unit tender. Rated at 3,600 hp, the locomotive would have fuel for thirty hours of operation. A 7,200-hp locomotive could be obtained by coupling a second A-unit at the rear.





Coal bunker with permeable metal fabric bottom would be one part of the complete fluidized coal-handling system on the gas turbine locomotive.

WHAT IS LDC?

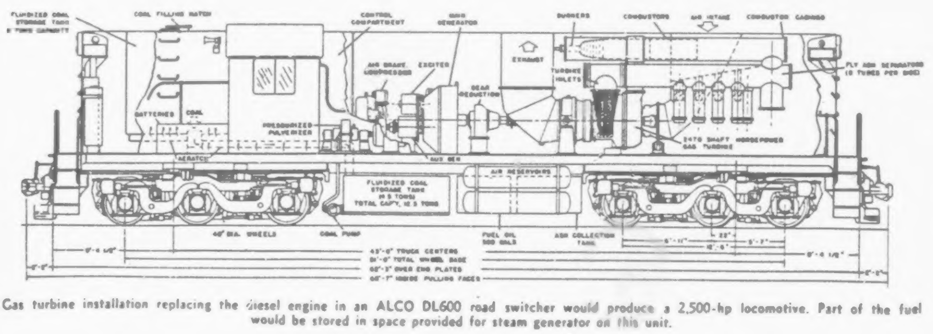
In 1945, a group of eastern railroad and coal company executives established the Locomotive Development Committee. Formed as a part of Bituminous Coal Research, Inc., LDC was to develop a locomotive capable of burning coal more efficiently than the 40,000 steam locomotives then in service.

The problems that confronted LDC in producing a coal-fired open-cycle gas turbine have been summarized as follows:

Feeding coal of suitable size to a pressurized combustion chamber under instant control at rates ranging from 500 to 5,000 lb per hr.

Burning the coal with a ninety per cent combustion efficiency with temperature rises from 200 to 900 deg F and outlet temperatures from 700 to 1,300 F.

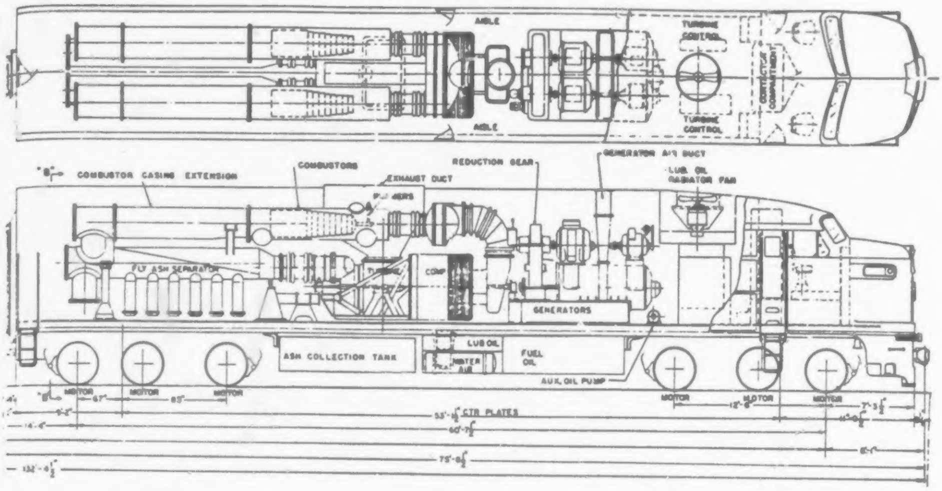
Prevention of troubles caused by the ash content of the coal.



Gas turbine installation replacing the diesel engine in an ALCO DL600 road switcher would produce a 2,500-hp locomotive. Part of the fuel would be stored in space provided for steam generator on this unit.

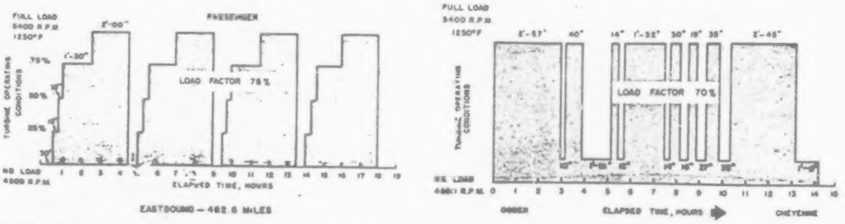
TURBINE LOCOMOTIVES: Coal

POWER UNIT



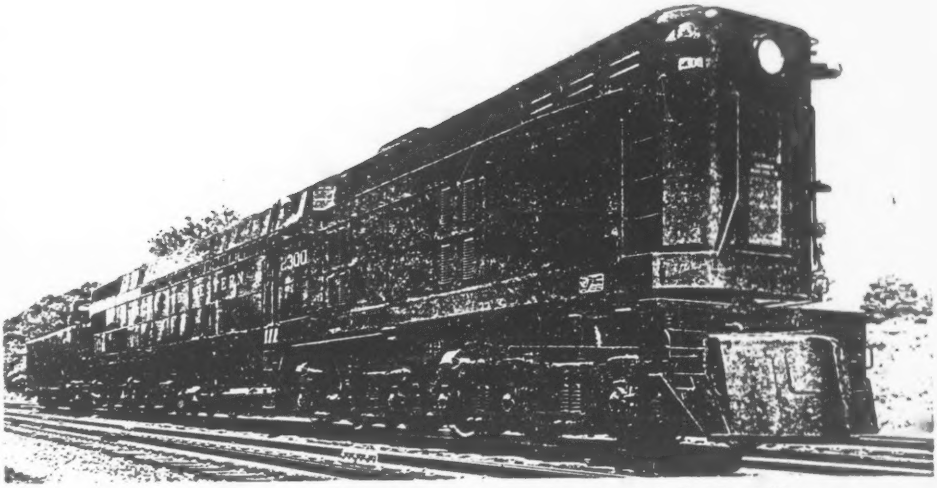
During 1,421 hours of the 1955 coal-fired test program at Dunkirk, N.Y., 4,111,398 hp-hr were produced with an overall efficiency of over eighteen per cent at an average load factor of 81.7 per cent.

	HIGH LOAD		LOCOMOTIVE CYCLES						TOTAL	
	1/15 - 4/19 5/24 - 6/9 6/30 - 7/22		NEW YORK CENTRAL 4/20 - 5/23		UNION PACIFIC 6/13 - 6/29		NORFOLK & WESTERN 7/25 - 7/28		1/15 - 7/28	
	HOURS RUN	TONS BURNED	HOURS RUN	TONS BURNED	HOURS RUN	TONS BURNED	HOURS RUN	TONS BURNED	HOURS RUN	TONS BURNED
POC. NO. 5	335:41	540.95	42:25	59.18					378.06	600.13
PITT. NO. 8	[illegible]	863.80	232:40	329.86			49:57	76.50	799:20	1270.15
UNION PACIFIC					343:32	270.00			343:32	270.00
TOTAL	852:37	1412.75	275:05	389.03	343:32	270.00	49:57	76.50	1421.11	2248.28
AVE. LOAD, HP	3200		2571		2253		2560		2894	
AVE. COAL RATE LB. PER HR	3314		2830		2699		3050		3164	
TOTAL HP HR	2,727,638		707,302		548,606		127,872		4,111,398	
LB. PER HP HR	1.036		1.10		1.20		1.19		1.09	
THERMAL EFF., %	18.80		18.25		16.1		17.5		18.20	
LOAD FACTOR, %	90.27		72.6		65.6		72.3		81.7	

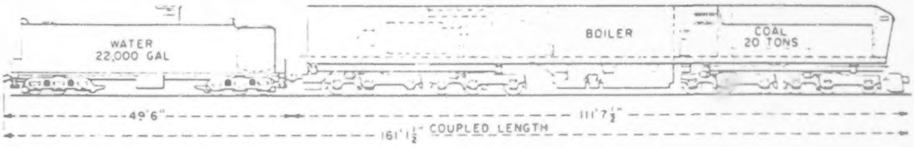


Examples of the load cycles imposed on the Dunkirk gas turbine to reproduce typical New York Central and Union Pacific road locomotive operations.

TURBINE LOCOMOTIVES: Steam



"Jawn Henry"—4,500-hp coal-fired steam-turbine-electric freight locomotive of the Norfolk and Western



Characteristics of the N.&W. Experimental Coal-Fired Steam Turbine-Electric Freight Locomotive

Wheel arrangement	6-6-6-6
Road number	2300
Rated horsepower at turbine shaft	4,500
Starting tractive force, lb.	175,000
Rated continuous tractive force (9 mph), lb.	144,000
Rated maximum speed, mph	60
Wheel base, ft.-in.:	
Rigid	13-0
Total engine	96-5½
Total engine and tender	1-47-3½
Driving wheels, diameter, in.	42
Length, ft-in.:	
Over couplers	111-7½
Tender over couplers	49-6
Locomotive and tender over couplers	161-1½

Weights, lb.:	
On drivers	807,000
Tender, loaded, lb	365,000
Tender, empty, lb.	180,800
Locomotive and tender, lb.	1,172,000
Boiler, water tube type	B&W, natural circulation
Steam pressure, psi.	600
Steam temperature, deg. F	900
Stoker	Standard Type BK
Coal capacity, tons	20
Water capacity, tender, gal.	22,000
Turbine, generator, motors	Westinghouse
Roller bearings:	
Locomotive trucks	Timken
Tender trucks	SKF

Senator **Warner**. I thank you, Mr. Kuntz, for a valuable contribution. You have come a long way to provide an important documentation for this record. I express appreciation on behalf of the Senate Energy Committee as I do to all witnesses. Particularly those at the last. I thank those that have taken the time to be in attendance today. If there are any who desire to insert into the record any contributions to this subject, the Chair will consider that insertion. This record will be completed very shortly and I will send it up the ladder very quickly to the Senate Energ Committee, the Senate as a whole and, in particular, the coal caucus. We refer to that caucus as the instrument within the U.S. Senate to push coal related legislation. It is an informal grouping of Senators representing those States that have major coal interests, and it is a cohesive hard-working group on behalf of issues relating to coal.

Thank you for joining me in this quest to find alternative means by which to fuel America's rail system and particularly the use of coal in our locomotives. Also, we possibly will be consulting with the chairman of the financial group as the alternative facts are sent in.

If we have no further person to be heard, this session of the U.S. subcommittee is adjourned.

[Whereupon, at 12:53 p.m., the hearing was adjourned.]

APPENDIX

Additional Material Submitted for the Record

FROM: Isaac Harter, III
25 Barclay Road
Newport News, VA 23606

TO: John Warner, United States Senator
Washington, D.C. 20510

SUBJECT: Coal Fuelled Railway Systems

For: Information and Action

Sir: I have read several news articles recently concerning your support of returning a larger proportion of the national and private railways to coal fired propulsion systems. I have also believed that such an approach would not only reduce the consumption of petroleum fuels, but would be more economical to the railway operations; particularly in areas where suitable steam coal is abundant or forms part of the railway load market.

I am presently a Senior Test Engineer at Newport News Shipbuilding, and as such, am involved with a wide variety of mechanical systems, including steam propulsion and auxiliaries. As a private hobbyist, I constructed and operated our own twenty eight foot, coal fired steam yacht; in addition to having been associated with "live steam" interests for over twenty years. On this basis, may I offer some suggestions for your consideration and forwarding to the appropriate parties for inclusion in their deliberations:

1. It is unlikely, that even if a substantial number of steam locomotives still exist in "mothballs", that they could be returned to commercial operation without extensive overhaul and refit. Even if corrosion and past wear and tear were at a minimum, the major problem would be locating and/or manufacturing replacement spare parts. The heavy machine shops once used to build and maintain the engines of the 1930's and forties have long ago been torn down and converted to other service. It must be remembered that enormous machines, presses and jigs were necessary to work on these big locomotives, where few parts weighed less than two hundred pounds. The other, (and more irreparable) problem would be to locate the men who used to build and repair the steam locomotives. Most have retired or passed on, and with them has gone the special knowledge and skill that was required to fit and groom the locomotives of the past.

2. The heart of the (reciprocating) steam engine is the cylinder-piston-valve assembly. By the end of the nineteenth century, the theory and practice of design and operation of nearly all services of steam engine had been advanced as far as it would ever go. Steam behaves according to strict principles of physics, and once this was finally understood, the machines were tailored to harness the steam as efficiently as possible. All that remained to be developed were newer and better materials, (stronger, lighter, less corrosive, longer wearing) and better methods of control and instrumentation. The process of steam generation (boiler design and construction) left more room for improvement as better materials and assembly methods were developed. It is in the area of boiler design and steam management that a new project will need to concentrate its efforts.

3. At the other end of the steam engine system is the power transmission arrangement, typified in most steam locomotives by the great piston and

connecting rods which rose and fell alongside giant driving wheels, quite like the muscles and legs of some giant beast. The energy of steam expanding in the cylinders was converted to reciprocating motion, which was mechanically converted into rotary motion. The system was quite simple and direct, but limited to a relatively narrow range of speed and load. It was also very difficult to keep clean and lubricated. The large masses of metal changing direction with every revolution caused high rates of wear not only to the engine parts, but to the railway itself, and was wasteful of energy.

The massive reciprocating motions of steam engines in mills, ships and locomotives were directly descended from the original pumps and walking beam engines of Watt and Newcomen. A few chain drives,(to speed up shaft revolutions or to slow down and increase torque,) were tried in various applications, but these were terribly noisy and wore out quickly due to the difficulty in correctly lubricating all those moving parts. If the question now arises; "why not use a "gear-box" the way cars and motorboats do, or for that matter, diesel locomotives," the answer is simply that the "gear-box" had not yet been invented that could handle the power of the steam engine without frequent breakdown or burn-out.

Only recently, have materials been developed which allow the manufacture of reduction gears or speed increasers which can handle high horsepower loads with any any degree of reliability. Even now, it is possible to build gear transmissions with a "reverse" capability only in small sizes. Ships with reduction geared turbines must still have a separate reversing turbine, and large diesels must be built "directly reversing" like the steam engine, which can be stopped and restarted in the other direction by simply changing the valve order. The problem arises when the steam engine is stopped because it cools off when steam is not applied. It must be carefully warmed up and vented when restarting to remove the water which condenses within the engine and which can cause damage if the engine is started too quickly. The better system would allow the steam engine to run at a constant speed; to "idle" when not under load and maintain its running temperature quite like an auto engine. When it was desired to move ahead or back, the transmission is simply shifted into the desired power range and direction.

All of this sort of thing had to wait for modern alloys, lubrication and design concepts. One of these is the Hydrostatic (hydraulic)transmission which allows power output in either direction over an infinite range of reduction ratios while being powered by a constant directional power source; gasoline, diesel, steam or electric engine. The hydrostatic transmission is the ultimate "automatic transmission" and is used in giant earth movers, tractors and other heavy power equipment, as well as lawn and garden tractors, conveyors, shipboard gun and missile launchers, and recently, some experimental automobiles. It is an expensive system to build, using modern materials and precision machining techniques, but once bought, the units are extremely reliable and nearly maintenance-free.

The hydrostatic transmission allows power to be transmitted to all of the wheels of the locomotive much the same fashion as in the diesel-electric locomotives presently in service. Hydraulic motors are used instead of electric motors, and a variable displacement, reversable hydraulic pump is used in place of an electric generator. I would expect that higher torques, greater load range and lower energy losses would be the advantages of a locomotive with steam engine-hydrostatic drive.

A steam engine-electric generator/motor drive system similar to the present diesel electric drives would probably be cheaper to build and more within the present capabilities of shops and personnel to maintain and operate. The infinite range of power transmission would not be as great (as hydraulic) and there are certain energy losses in translation from steam to mechanical to electric and back to mechanical power.

4. A steam-electric system would probably be the simplest arrangement and more in line with present practice. In fact, the drive motors, gears and axles would probably remain the same as with the diesel power units, thus simplifying training, maintenance and parts inventory. It is easier and less messy to couple up power units using electrical cables instead of hydraulic lines, when making up a train of several steam generating units and engine units.

Electric power for lighting, auxiliary (pumps, fans) and control systems will be needed in any system, so the more integrated the system, the better. A source of constant frequency, (60 hertz) power in voltages of 440, and 120 will be required for "Hotel" and auxiliary train services. Whether the steam engines drive a hydraulic transmission pump or a propulsion generator, a separate service electric power generator(s) will be required, independant of the propulsion arrangement. A small diesel/electric generator should be fitted for emergency and start-up service.

5. The steam engine should be located in a separate "car" from the steam generator or "boiler" car. Modern flexible piping now allows us to do this, where before, the engine and boiler were all in one unit. Actually there should be three units or unit types: The front or "A" unit would contain the cab for the engine drivers, the overall system controls, the engine controls the steam engine(s) and their attached generators or hydraulic pump transmission, and whatever steam engine/auxiliary generator(s) are required.

Behind the engine or "A" unit, is a "B" unit containing the coal fired steam generators; two, even as many as four separate boilers, together with their own control systems and an engineer to keep a watch on things. Behind each "B" unit is the "C" or coal tender, which carries bulk, mine coal and the plant water supply as in the earlier steam trains. The "C" unit is fitted with a self-unloader/conveyor (I would definitely recommend a hydraulic driver for this one), which is "quick-connected" to the "B" unit. The inter car conveyor then feeds the mechanical coal stokers leading to each boiler.

Depending on the size and service of the train, there might be two, three or even four "A" units. A sufficient number of "B" units are then coupled up to provide the steam required by the number of engines "on-line". A sufficient number of "C" units are then coupled up to serve the "B" units, depending on the number of "B" units and/or the length of the trip scheduled between coal and/or water stops. The idea is not new; it is known as the "modular concept", and allows one unit, say a "B" unit to be down for maintenance or repair while another takes its place, serving the "A" unit. Also, less boiler capacity need be used for light loads; for example: A commuter train of only a few light passenger coaches would need an "A" unit, one "B" and of course one "C". The run into town in the morning is relatively short and is in fact, "downhill". The run back, however, is the same length, but uphill and one more "B" unit is added for the required additional steam capacity. The engines in the single "A" unit are capable of the extra torque, given more steam. The short run in has hardly put a dent in the coal supply, so the single "C" unit is still adequate to serve both "B" units with plenty left over.

On the other hand, picture a long haul,heavy coal or ore train, doubled up and coupled up something like this: A*-A-A-A-C-B-C-C-B-C-C-B-C-C-B-C-C-B-C-C-B-C!!!

*Driver crew in the lead "A" unit only. The combined horsepower would be limited only as before by the drawbar strength of the coupler of the first car behind the engine.

Each unit, "A", "B" and "C" should be fitted with sand bins and wheel sanders and water tanks for feeding the boilers. All this adds weight to the driving wheels for better traction, since each wheel, whether "A","B" or "C" unit can be powered, either with conventional geared electric drive or geared hydraulic transmission.

6. Inter-unit transfer of coal between "C" and "B" units should be by conveyors located externally on each side of the unit. This will permit coal to be shifted in either direction with the conveyors split into service segments. The car units may be coupled in any combination without having to match up the "conveyor side" if conveyors are fitted each side. Dual conveyors offer a certain back-up redundancy in the event one conveyor breaks down. Being located externally, the conveyor units are readily accessible for inspection, repair, cleaning and/or de-icing.

Catwalks with handrails over the conveyors offer a means for personnel to walk the length of the engine units on either side.

7. In order to effectively make use of the nation's coal supply for rail fuel, the coal must be delivered and stored with a minimum of expense; that is, by conventional coal hopper car and stored outdoors in a "pile" or in open cars. In this manner, it is bound to get wet and freeze. This sort of coal, mixed with water, ice, rocks, shale and slate, (and occaisional tipple and conveyor parts), does not lend itself well to ball-mill pulverizing and blow-firing. I would avoid any notions of this, but rather stick to raw lump size coal that was used on previous auto-stoker fired locomotives.

8. The boiler (steam generator) must be designed for stoker fed, raw coal burned on a chain grate or some similar ash dumping device which can handle irregular lumps of coal, clinker, rocks, slag and spare parts. Otherwise, we are going to spend a lot of extra money on coal refining for engines with finicky tastes.

The boiler must be designed to handle water from practically anywhere along the right-of-way, with provision for blowdown of mineral buildup on the "watersides" as necessary, and treated with TSP and/or soda ash. The boiler will be a low-pressure, (600 PSIG, maximum) saturated steam unit which will not be as sensitive to water quality. The boiler will recover little or none of the water used.

9. I do not believe that it will be practical to attempt to design a fully condensing steam plant for a locomotive system, either for purposes of producing a low backpressure (partial vacuum) engine exhaust or for feed water recovery. I recall some years back, when Babcock and Wilcox Co. together with either General Electric or Westinghouse, experimented with an air cooled condenser equipped, steam turbine driven locomotive. The idea was to use vacuum level exhaust turbine/generators, supplied with steam from high pressure water tube boilers which used water of high purity. The project failed because under high horsepower/load conditions, the air cooled condenser could not condense all the exhaust steam, expecially when the outside (ambient) air temperature was warm. To make matters worse, the thing ended up stalled out on the prairie with the heat exchanger or "radiator" all choked up with locusts. Condensers are used on ships because it is essential to conserve fresh water at sea, and the needed exhaust vacuum can be generated rather easily with all that outside sea water as an excellent heat exhange transfer medium. Locomotives should stick to atmospheric exhaust, low pressure steam, and be designed to take on water from tanks along the right-of-way.

10. Given relatively low pressure, saturated steam, with atmospheric exhaust, we can again address the matter of the steam engine. Without a vacuum exhaust, a steam turbine is not very efficient. I would recommend either a high speed, multiple expension reciprocating engine or, if not multiple expansion, then multi-cylinder, long stroke "unaflow" type. This type of engine would occupy essentially the same position and function as the diesel engine in present diesel-electric locomotives. The engine runs at more or less constant speed and direction, and drives and electric generator or other power transmission. In this case, the steam is supplied by another car or "B" unit. The steam engine would differ

very little from its predecessors in power plants one hundred years ago, except that it would enjoy better cylinder packings, rods of "Monel", lighter alloys, and better bearings. Certainly, it would have a better lubrication system, and practically all moving parts should be enclosed to keep dirt out and to prevent lubricant from being flung about the "engine room".

11. Controls and monitoring of all aspects of the steam and engine system should be well within today's state-of-the-art, using electronic sensors, indicators and automated systems management. For example: The old-style Steam Engine Indicator was used to measure the performance of an individual steam engine cylinder using a complicated linkage of cords, springs, a paper "card" on a recorder drum and pen-and-pencil calculations. Modern electronic transducers can do all this and more, many times a second, over dozens of engine functions, and do it continuously. The results are fed into a microprocessor and the engine timing, steam flow and temperature are all monitored and adjusted automatically.

The essential ingredients for an entire coal-fired train system are already available; some are new, and some are the same proven "old" methods that have been in use before and now on the railways.

The foregoing comments and observations are by no means unique and reflect what I would expect any well run engineering study to at least consider for both merits and disadvantages. I submit these ideas for whatever worth they may be to anyone involved in the project. I believe that our abundant coal resources should be used wherever it is practical and economical to do so.
An updated coal-fired locomotive system should be well within our capability to develop and operate, not only on the railways of this Nation, but on those of other nations who have abundant coal reserves but little petroleum. American designed and built locomotives would be a welcome source of export revenue. I wish you luck in your efforts, and hope that my comments can be of some help.

Very truly yours,

Isaac Harter, III

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February 3, 1984

The Honorable John W. Warner
United States Senator from Virginia
United States Senate
Washington, D. C. 20510

Dear Senator Warner:

Thank you very much for your courtesy, in response to my letter of December 28th, and in writing me on January 16th (received February 2nd), appending Transcripts of your Hearings of November 28th and December 20th; also your opening Statement for your further Hearing of January 9th on, "Reintroduction of Coal as Fuel for Railroad Locomotives".

This material is of intense interest to me as the subject has been my major activity for the past five years. I regret not having known about your Hearings as I would have asked you for an opportunity to participate.

I am appending a Position Statement of December 2, 1982 on, "Choice of a Steam Turbine Electric Design", which I hope will be of interest to you and your Staff people involved.

I would be happy to come to Washington and discuss our proposed design with you and/or your Staff.

With kind regards.

Sincerely yours,

PERRY M. SHOEMAKER, President

PMS:1
attachment

December 2, 1982

SHOEMAKER & ASSOCIATES, INC.
RE: CHOICE OF A STEAM TURBINE ELECTRIC DESIGN

INTRODUCTION

S&A reached an early conclusion that the economic advantages of using coal as an energy source for rail transportation are so compelling that the appropriate question is the means of using coal in an environmentally acceptable fashion. Fundamental to this conclusion is that world demand and availability of energy resources will continue indefinitely the wide spread in energy unit cost between coal and liquid fuel whether refined crude petroleum, liquefied natural gas, or liquefied from solid fuels, including coal. S&A believes strongly that the spread will remain great which in the United States is from six to ten to one. Accordingly there is an opportunity for the railroad industry to take economic advantage of this differential, an opportunity not available to its motor carrier competitors.

S&A arrived at its decision to progress a steam turbine electric design after a deliberative process that explored in depth the available alternatives as viewed from a technical, economic and environmental viewpoint.

The above process has resulted in S&A promotion of a prototype locomotive with the following design characteristics:

-1. 9000 hp into alternator for traction.

-2. High adhesion with estimated locomotive weight of 1,200,000# on six-wheel trucks, with maximum weight per axle of 67,000# and continuous tractive effort of 271,800# at 9.16 MPH.

-3. A water tube boiler designed by ERK of West Berlin, of 600 psi, temperature of 900°F, output 110,000 lbs/hr.

-4. Fluid bed combustion as designed by Energy Equipment Co., Ltd. of England (a Petrofina enterprise).

-5. Condensing - using the proven Henschel Roosen system with air cooling to atmospheric pressure.

-6. Trucks, traction motors, rectifiers and other electrical components similar, if not identical, to equipment on diesel electric locomotives with which railroad maintenance personnel are familiar. Wheels 40" in diameter.

-7. Coal capacity of 45 tons* and water capacity of 10,700 gal. permitting 8 hours operation at full load and 15 hours operation under half load over average terrain.

-8. TIA (France) water treatment system so successful on SNCF.

-9. Cab on main unit and similar control cab on rear end of condenser unit.

-10. Dynamic braking.

-11. Maximum speed of 70 mph; gear ratio 74:18.

-12. Power unit length over couplers 116'6" with 65'0" pivot centers.

-13. Condenser unit length over couplers 94'2" with 59'8" pivot centers.

-14. Total locomotive length over couplers of 207'8".

-15. Maximum curvature 18°; Clearances meeting AAR Mech. Div. Plates C & C-1 as revised March 1st, 1971.

-16. Compatible with diesel electrics for "MU" operation.

*Note: Locomotive horsepower can be reduced, if a specific usage is anticipated, to approximately 6,000. For this the number of traction motors can be reduced or the 18 motor design may be retained.

The criteria developed for the prototype locomotive design can be modified to increase coal capacity to approximately 75 tons and water capacity to 20,000 gals., but a third unit would be required.

CRITERIA FOR RAILWAY LOCOMOTIVE

1. Reliability - This factor is, perhaps the most important. Long developmental periods, while reliability problems are being resolved, would result in the railroad industry being denied early realization of the large fuel savings available. Accordingly S&A decided that state of the art proven technology should be employed and that the design should incorporate the maximum number of proven components procurable. Railroads will buy new power in large numbers only when demonstrated reliability is achieved.

2. Compatibility with Diesel Locomotives - S&A believes there is little early likelihood that coal burning locomotives will totally replace diesels in the foreseeable future. The diesel, particularly in smaller units, is ideal for light coal applications such as yard and industrial switching and local service. Additionally, even if there should be a desired relatively rapid replacement of diesels for heavy freight service, where the impact of diesel fuel cost is so evident, it will take many years for the process to take place. Accordingly a replacement locomotive should be compatible with diesels for both operating and maintenance practices. Being able to use diesels and STEs in single consists provides operational flexibility.
3. Locomotive Maintenance - As locomotive maintenance cost is a major cost item it should be carefully considered with a goal of reducing expenses. In addition, the design selected should use proven components available from more than one source if possible. Alternative sources are important to insure reasonable price, service, and continuing effort by suppliers to improve product quality. To the extent feasible the design should minimize moving parts which are both expensive to replace and tend to impair reliability.

   A minimum impact on a carrier's need to retrain personnel to both operate and maintain a new locomotive is desirable. Likewise, use of existing shops, equipment and trained manpower is economic.
4. Locomotive Servicing - A new locomotive use should not impose a major servicing facility requirement. Water and coal capacity should be sufficient to avoid the installation of but a limited number of coal, sand, water and ash disposal facilities.
5. Thermal Efficiency - The design should maximize the use of proven technology to achieve the best possible thermal efficiency with varying characteristics and quality of coal.

ALTERNATIVES CONSIDERED

S&A reviewed thoroughly available technology to determine what alternatives could be reasonably considered. There are a number of long term potential~~-deve~~lopments that are encouraging such as the "Sterling" engine and particularly, advanced designs of gas turbines. Unfortunately most of these alternatives require the development of new materials and equipment such as high temperature heat exchangers that are not presently available and will take a long time to develop.

As a practical matter S&A concluded there are only three current candidates using coal as an energy service that can be progressed within a reasonable time frame.

Electrification is obviously a technically practical choice and would appear to be an ideal solution as coal could be efficiently combusted in power plants and any environmental problems involved in burning coal in locomotives could be avoided. The capital cost involved, including catenary construction, bridge and tunnel clearance modification, sub-station construction, and power distribution facilities in combination with long distance "line losses", results in very little of the North American railway lines being candidates. S&A believes at best only 6 to 8 percent of such lines are even candidates and it is probable that government funding would be required. Even so, the speed at which it can be realized involves such a long time-span in terms of achieving a substantial electrified mileage that for the next 20/30 years there will be scope for interim motive power solutions such as STE.

This leaves, in the short term, only two possible candidates for wide operation - the steam turbine electric or a reciprocating design. It would appear environmental concerns can be met with either design.

STE SELECTION

Electric Traction

The very high starting and low speed tractive effort characteristics of electric traction are very desirable advantages available with diesel electric operation. This characteristic is most advantageous in heavy freight service, particularly in the handling of unit trains. Such operation involves high fuel consumption where the maximum economic advantage can be obtained by the use of coal as fuel.

The STE will be able to use existing traction motors and related electrical equipment thus taking advantage of the considerable progress made over the past twenty years in the improvement of reliability and maintenance history. Various manufacturers can be selected for these components with the obvious benefits in pricing and service that competition brings.

Electrical transmission also permits the steam turbine to operate essentially as a constant speed machine, thereby operating within its most efficient speed range. Turbine design and reliability have improved continually for many years as a result of both marine and stationary applications and is readily adaptable to locomotive application. Buffing loads in fact are not as severe in a railway application as are commonly experienced in marine applications.

Steam turbine technology has developed high pressure, high speed, machines which are now available from several sources. They are of proven reliability, and permit high power to be generated from a single prime mover. Medium size turbines can achieve linear steam consumption rate/power characteristics over a wide range of power outputs when working in their efficient speed range. These technical developments are what have permitted S&A to provide 9000 horsepower in one locomotive. As a turbine operates with very few moving parts, compared with diesel or reciprocating designs, maintenance experience is anticipated to be most favorable resulting in probable significant reductions in maintenance expense for labor, part replacement, and component repair.

Compatibility of operations with diesel electrics is very important. An STE can be readily operated in a single locomotive consist of both, utilizing compatible control equipment. Wheel slip control equipment and dynamic brake equipment will also be the same, or very similar, to that employed by present diesel electrics.

Maintenance advantages are also significant in that electrical repairs and servicing will be identical or similar to that required for diesels' electrical equipment. Accordingly existing shops can be used, only requiring modification to handle the coal handling, fluid bed, boiler and turbine equipment - not a large investment requirement as this equipment has few moving parts and should need only periodic maintenance attention.

Boiler Selection

Knowing that turbine support and efficiency require modestly high steam pressure and high temperature steam, A&A contacted major United States boiler makers, including Combustion Engineering, Babcock & Wilcox, Foster Wheeler and Riley Stoker. Experiencing a minimum of interest S&A expanded its search and found that EFK of West Berlin was interested and anxious to design a suitable water tube boiler producing 110,000# of steam per hour at 900°F at 600# psi. The boiler is of strong waterleg construction, self circulating and meeting the size and weight constraints of our locomotive utilization.

With the use of highly treated water, boiler maintenance is minimal.

Automatic microprocessor controls covering the boiler, the turbine and the fluid bed combustion system provide both safe and effective operation.

Fluid Bed Combustion

Fluid bed combustion technology is relatively new and not well known or applied in North America. However, it is well advanced in Europe, and sufficiently developed to warrant inclusion in the STE design.

Fluid bed combustion has a number of particular advantages:

-1. Fluid bed technology is generally recognized as the most promising means whereby environmental concerns can be satisfactorily addressed for smaller combustion systems where it is not feasible to employ large and expensive scrubbing equipment.

Nox emissions are not a significant problem, as one of the virtues of fluid bed technology is that combustion in the bed takes place at relatively modest temperatures (1550°F) and accordingly nox production is minimal.

Much developmental work is now underway, including use of limestone as bed material, and lime injection into the bed and into the secondary combustion zone, so that sulphur emissions can be minimized.

For a locomotive application the challenge is to be confident that technology is economically available to meet emission standards that are likely to be imposed. Present standards are not difficult to meet. Developmental work to insure that sulphur and particiculate emissions can be satisfactorily handled will continue, and S&A is confident satisfactory results will be achieved.

-2. The fluid bed combustion system can utilize standard size coal under 1½ inches and use a wide range of coal types from lignite and Western coals to Eastern higher BTU coals with the same size fuel bed dimensions. This is due to the fact that an operating fluid bed has approximately only 15% fuel within the bed, the remainder being composed of inert bed material. Accordingly there is wide latitude in the characteristic of fuel used. In fact, solid fuels other than coal can be used, or can be mixed with coal.

-3. The fluid bed operation employed by the S&A design has a zoned operation of the combustion bed, and thus with variable speed blowers for each zone, permits immediate turndown capacity with an immediate "heat lock" applied when a "slumping" condition is imposed. The system is more responsive than alternative combustion systems. "Turn up" is likewise rapid as entrapped combustible gas is released for combustion when a bed is reactivated.

-4. A fluid bed operates in a fashion that the ash is contained in the combustion exhaust stream. As it consists of fine spherical particles, there is a "ball mill" effect avoiding the need for periodic boiler and tube surface cleaning. Operating fluid beds in the United Kingdom have required no cleaning of boiler fireside surfaces for as much as a full year of continuous operation.

-5. With a fluid bed, ash is removed by use of grid arrester equipment from the exhaust stream at the head of the boiler (after recycling to insure a very high percentage of the combustibles being oxidized). The ash material will be pumped into storage tanks under the condenser unit and pneumatically removed at servicing locations by pumping the material to an off-track storage facility, or logically directly into a covered hopper or truck trailer for subsequent movement to a user of the material. There will be no return to the messy and expensive traditional ash disposal methods common in former steam days.

-6. The operation of the coal using fluid bed, boiler feed water addition and turbine operation will be completely automated through the use of microprocessor equipment. Fluid bed systems operated in England have been unmanned for a considerable period in a completely safe manner.

THERMAL EFFICIENCY CONSIDERATIONS

An STE design fired by a fluid bed combustor will be substantially more efficient than the reciprocating designs common in the days of steam. A large portion of the BTU content of coal, perhaps in excess of 20%, was blown out the stack which under today's conditions would be wasteful and environmentally unacceptable. Energy Equipment Co., Ltd. - S&A's supplier of the fluid bed combustor - has installations operating in commercial service where the carbon loss is approximately 3½% (2½% of the coal) with a substantial portion of the loss found in the ash as opposed to being exhausted to the atmosphere.

As previously indicated the time capability of a zoned fluid bed operation minimizes the source problem of wasted BTUs in conventional combustion when adjusting load.

Steam turbine efficiency should not be confused with gas turbine characteristics where a significant efficiency decline occurs at part load. Coupled with electric traction the steam turbine will essentially be a constant speed machine operating within its most efficient speed usage.

Thermal efficiency of the proposed locomotive, with steam conditions of 600 psi and 900°F, with exhaust from main turbine at atmospheric pressure and about 300°F, will be about 15% for the boiler and turbine and about 11% at the rail, after allowing for power absorbed in the electrical transmission system and auxiliaries. These figures are based on a theoretical Rankine steam cycle efficiency of 25%, turbine efficiency of 75% and boiler efficiency of 80%, both the latter being quoted on a conservative basis. The overall thermal efficiency of about 11% should be maintainable over a wide range of power outputs from full power down to a load factor of 20% or less.

CONDENSING DESIGN

S&A has incorporated a condensing design recognizing that water usage in certain geographical areas is unacceptable as to both quality and quantity and that provision for frequent water servicing locations is an undesirable limitation of utilization.

Treated water is an important necessity for boiler operation. On board treatment may be incorporated in S&A's prototype design, but for a railway application operating a fleet of STEs it is expected that stationary treatment will be more economical. The water capacity provided on the locomotive will be directly related to the coal capacity, to the end that the need for each at a servicing point will be reasonably balanced as to anticipated usage.

The proven Henschel Roosen system which we have chosen condenses to atmospheric pressure and provides a recycling of about 85% of water for boiler use. The other 15% is diverted from the main turbine exhaust and used to supplement primary air in the fluid bed combustor.

RESPONSIVENESS

STEs may be operated in multiple unit with standard diesel-electric locomotives with which they will be compatible, and will provide an equivalent degree of build-up of power output in equivalent controller notch positions; STEs having the same basic speed/tractive effort characteristics as diesel-electrics. When operating in multiple with diesel electrics, with an STE as the lead unit, control devices similar to those already used on diesel-electrics would insure that STEs would operate at maximum load factor, with trailing diesel units cut in only when required, to achieve maximum savings in fuel costs.

HISTORICAL PERSPECTIVE

The concept of a steam turbine electric is not new. Experiments were carried out in England and Europe more than 50 years ago and in this country after World War II on the C&O and the N&W.

The S&A STE, however, bears little practical resemblance to the original efforts. Combustion and boiler technology have changed dramatically in the 30 year interval. Boiler operating pressures of 1200 psi are now common and high speed turbine development permits packaging of high horsepower in a locomotive. S&A's boiler will operate at 600 psi, a conservative pressure compared to present marine and stationary boiler applications. While adva ced metallurgical developments and welding techniques have made it feasible to operate with higher pressures, we have been advised by competent authorities that in the condition of locomotive service, where it is essential to reduce maintenance and inspection costs (also initial cost) to a minimum, S&A's choice of boiler pressure (600 psi) and temperature (900°F) is justifiable.

The economy of scale opportunities is thus very great, permitting a single STE to replace three standard 3000 hp locomotive units now in common use in heavy freight service.

Perhaps one of the most important technological changes is the opportunity to incorporate automatic process control so that coal, feed water, boiler and fluid bed operation, and steam demand,can be completely automated, eliminating human error, maintaining high efficiency and providing diagnostic monitoring of components and operations.

The S&A STE while not new in concept is very different indeed from any past effort.

FURTHER DEVELOPMENT POTENTIAL

The S&A locomotive design can readily be modified to create a 6000 horsepower locomotive but still with full adhesion and high tractive effort from 18 traction motors.

Future improvements in emission control may require a third unit to house equipment involved. This would provide room for doubling the coal and water supply readily providing a 1000 mile operating range - an attractive potentiality for many railroads.

SHOEMAKER & ASSOCIATES, INC.

SwRI-5361-003

ALTERNATIVE FUELS FOR MEDIUM-SPEED DIESEL ENGINES (AFFMSDE) PROGRAM

THIRD RESEARCH PHASE FINAL REPORT

Slurries, Emulsions and Blended Fuel Extenders;
Cylinder Wear Measurements, Staged Injection

Prepared for

U.S. Department of Energy
Federal Railroad Administration (DOT)
and
The Association of American Railroads

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August 1983

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Association of American Railroads

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO HOUSTON

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16. Abstract (Limit: 200 words)

This report describes the third year of research activity on an ongoing research, development and demonstration effort to investigate the use of alternative fuels for medium-speed diesel engines. The first and second years of the project (Phases I and II) are the subjects of earlier reports available through NTIS and AAR.

Tests were performed using laboratory medium-speed diesel engines to define the ability of these engines to operate on alternative fuels, the fuel property limits that the engines can tolerate, the problems associated with alternative fuels use, and methods to improve fuel tolerance and to overcome the problems identified. The fuels studied during the Phase III program were alcohol-in-diesel fuel emulsions, water-in-diesel fuel emulsions, sunflower oil/diesel fuel blends, No. 6 fuel oil/diesel fuel blends, and a carbon black/diesel fuel slurry. Also studied were methods to measure cylinder liner and piston ring wear rates in a short period of engine operation. Finally, staged injection was investigated as a means to improve engine performance on low cetane number fuels.

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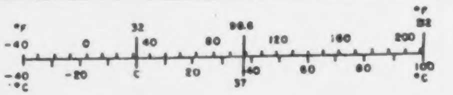
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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LIST OF ABBREVIATIONS

AAR - Association of American Railroads
AFFMSDE - Alternative Fuels for Medium-Speed Diesel Engines program
API - American Petroleum Institute
ASTM - American Society for Testing and Materials
Bhp - Brake Horsepower
BSFC - Brake Specific Fuel Consumption
BTDC - Before Top Dead Center
BTU - British Thermal Unit
C - Centrigrade
CA - Crank Angle
cc - cubic centimeter
cSt - centistokes
deg. - degree
DF-2 - No. 2 diesel fuel
DOE - Department of Energy
EGT - Exhaust Gas Temperature
EMD - Electro-Motive Division
EP - End Point
F - Fahrenheit
FRA - Federal Railroad Administration
GE - General Electric
HAN - Highly Aromatic Naphtha
IBP - Initial Boiling Point
in - inch
inj - injection
ITP - Integrated Test Plan
lb - pound
max - maximum
mg - milligrams
min - minimum

LIST OF ABBREVIATIONS, Cont'd.

mm^3/stk	cubic millimeters per stroke
MSDE	Medium-speed Diesel Engine
NRCC	National Research Council of Canada
p&b	plunger and barrel
RPM	revolutions per minute
SAE	Society of Automotive Engineers
SFO	Sunflower Oil
SRC	Solvent Refined Coal
SwRI	Southwest Research Institute
TDC	Top Dead Center
USDA	U.S. Department of Agriculture
vol	volume
wt	weight

1. EXECUTIVE SUMMARY

This report encompasses the third research phase of the ongoing "Alternative Fuels for Medium-Speed Diesel Engines" (AFFMSDE) program which began at SwRI in August 1978. Phases I and II are the subject of separate reports.(2,3) The Phase I report describes the first year of research work which dealt with the use of low cetane number, high viscosity, and extended distillation range of off-specification diesel fuels, as well as two non-diesel fuels, methanol and a simulated coal-derived fuel. The Phase II program extended this work. Off-specification diesel fuels were further tested and attempts were made to improve performance of these fuels through minor engine modifications. Ethanol and methanol were used as diesel fuel extenders in the form of emulsions with No. 2 diesel fuel. Synthetic fuels derived from shale oil and coal were evaluated. A highlight of the Phase II program was the addition of two 12-cylinder medium-speed diesel engines to the SwRI facility to complement the two-cylinder medium-speed research engine used throughout Phases I and II. The Phase III program extended the alcohol emulsions test to the two 12-cylinder laboratory engines. Also studied during Phase III were methods to improve engine operation on low cetane number fuels and techniques to measure cylinder wear rates in a relatively short duration in the laboratory. New fuel types evaluated were slurries of solid materials in diesel fuel, blends of No. 6 fuel oil and diesel fuel, blends of vegetable oils with diesel fuel, and emulsions of water and diesel fuel.

The AFFMSDE program is a multi-year research, development, and demonstration effort to investigate the use of alternative fuels in medium-speed diesel engines. This cooperative program began under the sponsorship of the Department of Energy. The Federal Railroad Administration (DOT) began contributing funding during the first year of the program. The Association of American Railroads (AAR) has been involved in program planning and review functions since its inception. The AAR contributed the two 12-cylinder medium-speed diesel engines through its member railroads during Phase II, and funding support for the Phase III work. The AAR is the sole sponsor of the Phase IV program, now underway.

Medium-speed engines are the prime power source for several important industries including rail and intercoastal shipping and power generation. Each of these industries relies on an adequate supply of diesel fuel. Should the supply be interrupted, as occurred in the 1974 oil embargo, these industries could be crippled. Thus, one or more alternative fuels must be sought to ensure an adequate supply for these emergencies. Also, since fuel bills for these industries are now a major percentage of their operating costs, low cost alternative fuels are being sought.

At this time, no one can precisely define the types of fuels that will be available in the future. Petroleum product specifications may vary in an attempt to optimize refinery output and reduce refining costs. Synthetic fuels are receiving increased attention and may come into common use. Unconventional fuels, such as alcohols or gaseous fuels, which are unsuitable for diesel engines without an ignition source, may be available. For this reason, a broad based approach is being taken to the alternative fuels investigation. The program encompasses all of the above fuel types for the purpose of examining both short- and long-term possibilities. The objectives of the program are to define the ability of medium-speed diesel engines to operate on alternative fuels and to define the problems of converting existing equipment to use selected alternative fuels. The operating characteristics of these engines using alternative fuels are being studied in the research stages of the program. These laboratory tests solve initial problems, define engine operating characteristics, and identify areas that need further investigation. Engine performance and emissions are being studied. Promising fuels will be selected for the development stage, which will bring engine hardware and related equipment from the research level to a state of more advanced design. Ultimately, the development work will permit operation of the full-size locomotive engines on alternative fuels under simulated locomotive duty cycle operation. Fuels will thus be screened for the final stage, which will be a demonstration in an in-service locomotive.

The experimental work is being conducted using three medium-speed laboratory diesel engines. The first of these is a two-cylinder, Roots blown version of the EMD 567B two-stroke engine constructed specifically for research. The other two engines, an EMD 645 E3 and a GE 7FDL, are current production, 12-cylinder, turbocharged diesels. The EMD 645 E3, like the two-cylinder EMD engine, utilizes the two-stroke cycle. The GE 7FDL operates on the four-stroke cycle. The two-cylinder EMD engine lends itself well to research work because of its small size and low fuel consumption rates. However, the power output per cylinder of this engine is only about one-half that of current production medium-speed diesels. It is not state-of-the-art and the results obtained differ somewhat from the high output turbocharged engines. As a result, the two-cylinder EMD is primarily used as a screening tool with which alternative fuel types are first evaluated. Fuel types that look promising are considered for use in the full-size laboratory engines.

Experiments conducted using the two-cylinder EMD engine during Phase III covered three areas:

1. Improvement of engine performance when consuming low cetane number fuels
2. Measurement of cylinder wear rates while operating on alternative fuels
3. Evaluation of new alternative fuel types

The use of low cetane fuels is of concern because of the general trend in petroleum products towards lower cetane quality plus the large number of non-petroleum alternatives that have low cetane ratings, such as alcohols and some coal-derived synthetic fuels.

A total of four alternative fuels were tested in the 12-cylinder engines during Phase III. These were alcohol/DF-2 emulsions, water/DF-2 emulsions, sunflower oil, and blends of No. 6 fuel oil and DF-2.

The findings of the Phase III program are summarized in the following sections.

1.1 TWO-CYLINDER ENGINE EXPERIMENTS

The objectives of two-cylinder engine low cetane number fuel testing were to improve engine performance using fuels whose cetane numbers were significantly degraded from the DF-2 specification and to obtain acceptable performance when burning fuels of a lower cetane rating than the engine can currently tolerate. ASTM D975 specifies a minimum DF-2 cetane number of 40. Tests revealed that the two-cylinder engine could tolerate fuels with a cetane number as low as 30 before significant changes in performance occurred. Below 30 cetane, knocking was detected and engine power and thermal efficiency decreased.

Several methods to improve low cetane number performance were evaluated during Phase II(3). These included intake air heating, fuel heating, increased exhaust backpressure and reduced intake boost pressure. These techniques were only marginally successful and did not significantly extend the cetane limit. However, a technique called "staged injection" proved to be very effective for eliminating knock at cetane numbers as low as 24. Staged injection is the injection of a small portion of the low cetane fuel early on the compression stroke, which acts as a pilot, igniting before injection of the remainder of the low cetane number fuel. The Phase III staged injection experiments attempted to further extend the cetane number limit by improving the method by which the pilot charge was injected. Alterations made to the pilot fuel spray pattern, spray orientation, and injection timings were quite successful, permitting knock-free operation on fuels of cetanes as low as 17.7. Engine power output and thermal efficiency were high for all of the low cetane number blends tested.

An attempt was made to operate the engine entirely on methanol using staged injection rather than a supplemental ignition source, such as a spark plug. This would extend the cetane limit to essentially zero. These tests were performed at a compression ratio of 20:1, rather than the 16:1 used for all the above experiments. The methanol staged injection tests were not successful: the methanol pilot charge could not adequately control ignition of the main charge to prevent severe knocking. A further increase in compression ratio would be needed for methanol staged injection to be feasible.

Attempts were made to control the initial rate of combustion and reduce knocking of low cetane number fuels using water emulsions. These were considered because of the research success of water emulsions in reducing fuel consumptions and smoke levels of smaller engines. The emulsions failed to reduce engine knock levels. In all cases, knocking increased with water content of the emulsions.

The second research area addressed through two-cylinder engine experiments was the measurement of cylinder wear rates when operating on alternative fuels. This task involved studying methods for estimating wear in relatively short periods of time using laboratory diesel engines to avoid conducting costly long-term laboratory or field wear studies. The short-term wear technique chosen for evaluation was spectrographic analysis of oil samples taken directly from the cylinder liner wall. This technique was extensively investigated using an EMD 567 series engine several years ago by the National Research Council of Canada.

The two-cylinder EMD engine was modified for direct oil sampling from the liner walls in the manner prescribed by NRCC. Slight modifications to the NRCC procedure were made to improve accuracy and repeatability of the wear data. Unfortunately, the wear technique did not prove successful on the two-cylinder EMD engine. A series of 100 hour duration wear tests were performed using No. 2 diesel fuel and a 1.0 percent sulfur diesel fuel. There was no detectable difference between the iron and chrome concentration of the oil samples during operation on these two fuels, even though the 1 percent sulfur fuel caused substantially higher wear rates. Several steps taken to increase the sensitivity of the wear measurement failed. It may be possible through further development work to increase the sensitivity to the needed level. The primary obstacles that must be overcome are low oil flow rates from the sampling holes in the cylinder liners and concentrations of wear metals in the oil samples that are at the lower limit of detection by spectrographic analysis.

The two new fuel types evaluated using the two-cylinder engine during Phase III were slurries of carbon black and diesel fuel and blends of sunflower oil and diesel fuel. Carbon black was chosen as the solid component for the slurry since it was less abrasive than coal, formed a relatively stable slurry with diesel fuel, and was commercially available in the small particle sizes needed. Bench tests were conducted on the fuel filtration, pumping, and injection systems prior to engine testing to determine the effects of the slurry on these components. Filtration of the slurry was not possible or practical; the slurry clogged filter elements almost immediately. Common gear-type fuel pumps and injectors wore rapidly on the slurries ranging in concentration from 5 to 15 percent weight carbon black. Two-cylinder engine performance was good on slurries containing up to 15 percent carbon black, but power output and thermal efficiency declined when consuming 20 percent. Inspection of the engine following slurry tests revealed extremely high piston ring and cylinder liner wear. The mechanism which caused the wear could not be determined based on the data recorded.

A fully refined sunflower oil (SFO) was evaluated during this program. The SFO was found to be of slightly lower heat content and cetane number than diesel fuel, but was suitable for consumption in neat form. Blends of SFO and diesel fuel in varying proportions, as well as neat SFO, were tested in the two-cylinder engine. Overall engine operation was quite good, the only shortcoming being a reduction in thermal efficiency. The main areas of concern for extensive sunflower oil use are its effects on crankcase lubricating oil, and carbon deposits from prolonged low load operation. Vegetable oils are one of the few non-petroleum fuel types that offer the potential for direct replacement of No. 2 diesel fuel. The vegetable oils are not economically viable at this time, but may be very valuable in a fuel shortage.

1.2 TWELVE-CYLINDER ENGINE TEST RESULTS

The maximum fuel viscosity that each of the full-size engines could tolerate in their standard configurations was determined through a series of tests in which fuel viscosity was varied independently of the other fuel properties. These limits were found to be considerably higher than the DF-2 viscosity specification. The data indicated that the fuel supply systems were the limiting factor in the use of a high viscosity fuel. The EMD fuel system could not tolerate the high pressure generated by fuel pumps when handling high viscosity fuels at low engine fuel consumption rates; fuel system seals began leaking. The General Electric engine was unable to ingest sufficient fuel to maintain full power output above a specified viscosity at each fuel consumption rate. The viscosity limits of the two engines ranged from 60 centistokes at rated speed and load up to 140 cSt at low speed/low load conditions. The fuel supply difficulties could be overcome by resizing fuel pumps and motors.

Unstabilized alcohol-in-diesel fuel emulsions were tested in the 12-cylinder engines. Both methanol and 190 proof ethanol were consumed. The amount of diesel fuel that could be replaced by either of the alcohols was limited by engine knocking. Up to 30 percent by volume of methanol and ethanol were tested. Severe knock occurred at these high alcohol inputs. Knocking was first detected at alcohol contents of approximately one-half this level. Thermal efficiency and power outputs were reasonably good on the EMD at all tested notches, and on the GE at Notches 6 and above. The General Electric engine did not perform well on the alcohol emulsions at Notches 2 and 4, generating high white smoke levels and low power outputs.

Water-in-diesel fuel emulsions were studied for their potential to reduce specific fuel consumption and exhaust smoke levels of the 12-cylinder engines. Small improvements in specific fuel consumption (BSFC) were recorded on the 12-cylinder EMD. These reductions amounted to a maximum of 2 percent at a low power output condition, to a minimum of .5 percent at rated speed and load. No benefits were derived from the emulsions in the GE at the low speed and load conditions, but a .5 percent BSFC reduction was recorded at rated speed and load. Exhaust smoke levels decreased as water content increased in both engines.

The sunflower oil evaluated using the two-cylinder engine was also tested in the 12-cylinder engines. A blend of 50 percent by volume sunflower oil and diesel fuel, as well as neat sunflower oil, were tested. The results verified the conclusions drawn from the two-cylinder engine tests. The fully refined sunflower oil could replace No. 2 diesel fuel and produce performance levels comparable to that of diesel fuel. Likewise, the fuel could be blended with diesel fuel in any proportion to extend the diesel fuel supply.

The final fuel type evaluated was blends of No. 6 fuel oil with diesel fuel. Use of heavy fuel blends has gained a good deal of interest recently due to the availability and low cost of No. 6 fuel oils. The properties of No. 6 fuel oils prohibit their use in neat form in exisiting engines. However, it is feasible to mix a residual with diesel fuel and produce a blend of acceptable quality. A guideline was developed to determine the amount of No. 6 that can be blended as limited by the fuel property tolerance limits of common medium-speed diesel engines. The blends produced according to the guideline were to be of suitable quality for direct replacement of diesel fuel in rail and marine applications.

No. 6 blends were mixed using two No. 6 stocks, one of poor quality and one of high quality, and both blends were tested in the full-size engines. The content of the poor quality No. 6 was 8.8 percent volume, and the high quality No. 6 was 17.9 percent. Engine power output and thermal efficiency decreased by as much as 4 percent in each engine on each fuel. Smoke levels were comparable to DF-2. A 48-hour continuous idle test was performed on the 12-cylinder EMD using the 17.9 percent blend. A significant buildup of carbon deposits as well as raw liquid fuel in the exhaust manifold resulted. Such deposits may lead to turbocharger destruction should an exhaust fire develop.

1.3 PHASE IV OF THE AFFMSDE PROGRAM

The Phase IV program to be completed during calendar year 1983 includes five program tasks. These are:

1. Conduct long-term laboratory screening tests on both 12-cylinder engines to determine the effects of heavy fuel blends on engine performance, durability, exhaust emissions, and operating characteristics. The purpose of the tests is to screen fuels before undertaking long-term locomotive tests. Various methods of measuring short-term wear rates in engine power assemblies will also be investigated during these laboratory experiments.

2. Conduct field tests of heavy fuel blends in line-haul locomotives. These tests will be managed and run by interested railroads with participation from the Association of American Railroads and SwRI personnel.

3. Develop the specifications for the injection parameters (orifice sizes, injection timings, etc.) for a staged injector for the EMD 2-567B engine.

Also, demonstrate the feasibility of constructing a single injector with staged injection characteristics.

4. Analyze and characterize candidate blended fuels that are potentially lower cost fuels. The objective is to investigate, through information gathering and lab testing, the possibility of using secondary blend components other than No. 6 fuel oils.

5. Conduct performance tests with both 12-cylinder engines operating on selected alternative fuels that offer the potential for near term use at lower cost relative to DF-2. The objective of this task will be to obtain basic performance, combustion, and emissions data for these fuels to evaluate whether more extensive laboratory and field testing is warranted. Fuels identified in Task 4 are potential candidates for these tests.

2. CONCLUSIONS

Tests were performed on laboratory medium-speed diesel engines to define the ability of this class of engine to operate on alternative fuels, and to define the performance and emissions characteristics of the engines under such operation. These tests constituted the third phase of an ongoing alternative fuels investigation. Three test engines were employed: a two-cylinder EMD, and two 12-cylinder turbocharged engines, an EMD 645 E3 and a GE 7FDL. Experiments conducted on the two-cylinder engine attempted to improve performance on low cetane number fuels, and to measure the piston ring and cylinder liner wear caused by alternative fuels. Slurries of carbon black in diesel fuel and blends of sunflower oil and diesel fuel were also evaluated using the two-cylinder engine. Five fuel types were evaluated on the full-size engines. These were emulsions of alcohol and diesel fuel, emulsions of water and diesel fuel, sunflower oil, heavy fuel blends, and high viscosity fuels. The viscosity limits of both 12-cylinder engines were defined through the latter series of tests.

A wide range of fuels have been tested in the AFFMSDE program since its inception in 1978. These fuels are summarized in Table 2.1. During the first phase of the program, emphasis was placed on defining the basic engine performance using alternative fuels. That emphasis has now shifted to studying particular fuel types that are potential low cost substitutes for No. 2 diesel fuel. A large data base has been developed on the performance and combustion characteristics of a wide range of fuel types. Sufficient experience has been gained through the development of this data base to predict the performance of many new candidate alternative fuels. However, little data is available in the areas of emissions, durability, and wear. These factors are essential for a complete and informed evaluation of an alternative fuel. Thus, the emphasis of upcoming programs will be in the area of long-term effects, which will eventually require extensive testing in an actual field operating environment to arrive at a true evaluation.

The conclusions reached from the Phase III program are outlined below:

Table 2.1 Summary of Fuels Tested in the AFFMSDE Program

Phase	Fuel Type	EMD 2-567B	EMD 12-645 E3	GE 12-7FDL	Field Test
I	Off-specification diesel fuels:				
	Low cetane	●			
	High viscosity	●			
	Boiling range	●			
	Simulated coal-derived fuel	●			
	Methanol	●			
II	Off-specification diesel fuels:				
	Low cetane	●	●	●	
	High viscosity		●	●	
	Synthetic fuels:				
	PARAHO DFM	●			
	SRC-II	●			
	Alcohol emulsions and solutions	●			
	Water/DF-2 emulsions		●	●	
	Low proof ethanol	●			
	No. 3 diesel fuel	●			
III	Sunflower oil blends	●	●	●	
	No. 6/DF-2 blends		●	●	
	Carbon/DF-2 slurries	●			
	Alcohol/DF-2 emulsions		●	●	
	Water/DF-2 emulsions		●	●	
	Low cetane optimization	●			
	Cylinder wear measurements	*	*	*	
IV	Staged injector design	*			
	No. 6/DF-2 screening tests		*	*	
	No. 6/DF-2 blends				*
	Low cost heavy fuel blends		*	*	

● - Items completed
* - Tasks in progress

Low Cetane Number Fuel Tolerance

The minimum cetane number that a medium-speed diesel engine can tolerate can be extended significantly through staged injection. Fuels possessing cetane numbers as low as 17.7 were tested in the two-cylinder engine without knocking and with good thermal efficiencies through staged injection. By comparison, audible knocking normally occurs at a cetane rating of approximately 30 for this same engine using standard injection equipment.

Water acts as a cetane number depressant when emulsified into a fuel. As a result, water emulsions have a detrimental effect when consuming low cetane number products, increasing their potential to knock.

Short-Term Cylinder Wear Measurement

This program was not successful in measuring piston ring and cylinder liner wear rates through spectrographic analysis of oil samples drawn directly from the liner wall of the two-cylinder EMD 567B engine. Short-term was defined as a test of less than 100 hours duration. It was concluded that severe engine operating conditions will be needed to accelerate wear and increase the concentration of metals in the lubricating oil for this sampling technique to be successful. Since such operation is at non-standard conditions, a correlation will be needed between the accelerated laboratory wear rates and actual field engine wear rates. Such a correlation can only be developed through extensive laboratory and field testing of the same fuel.

Slurry Fuels

Slurries are a potential means of consuming solid fuels in a medium-speed diesel engine. Extensive injection system and engine development will be needed before satisfactory performance and wear characteristics are achieved on such fuels. In light of the other alternative fuels available, the slurries are very low ranking, both as emergency and long-term substitute fuels. Slurries should not be considered for further evaluation in the AFFMSDE program unless new technology develops that improves their status.

Vegetable Oils

Vegetable oils offer potential as either a substitute or an extender for diesel fuel. The fuel properties of several of the vegetable oils are comparable to diesel fuel. The fully refined sunflower oil tested in the three laboratory engines generated very good engine performance. This is only the second non-petroleum fuel evaluated in this program that is suitable as a direct replacement for No. 2 diesel fuel in existing field engines, the other being a marine diesel fuel produced from shale oil. Vegetable oils are currently unattractive due to their high cost and low availability. However, they could play an important role in a fuel shortage if available.

The effects of sunflower oil, as well as other vegetable oils, on lubricating oils and engine deposits are unknown. Long-term studies of such effects are needed.

Twelve-Cylinder Engine Fuel Viscosity Limits

The viscosity of a test fuel was varied independently of the other properties by heating the fuel to determine the maximum fuel viscosity that both 12-cylinder engines could tolerate. The fuel supply system was the limiting factor in both cases. High pressures were generated by the fuel transfer pumps on the EMD, causing seals to leak at high viscosities. The fuel supply system of the GE was incapable of pumping sufficient fuel to the injection pumps to adequately supply the engine above a specific viscosity at each fuel consumption rate. The viscosity at which these limits were reached was considerably above the No. 2 diesel fuel specification on both engines. These limits ranged from 40 to 140 cSt, depending on the speed and load condition. The problems encountered could be easily overcome by redesign of the fuel supply systems.

There exists a viscosity limit above which combustion abnormalities will occur, as evident from a decline in power output of both engines at high viscosities at low speed/load conditions. Such limits should be defined if high viscosity fuels receive serious consideration.

Alcohol/Diesel Fuel Unstabilized Emulsions

The amount of methanol or ethanol that can be emulsified into diesel fuel is limited by engine knocking. The cetane number of the emulsion is proportional to the volume content of alcohol and diesel fuel, and decreases as the proportion of alcohol increases. A maximum of 30 and 25 percent volume of the alcohols were tested in the EMD and GE, respectively. Loud audible knocking was present at these alcohol inputs. Mild knocking was first detected at alcohol percentages of approximately one-half this level. Thermal efficiency of the EMD was comparable to baseline diesel fuel when operating on the alcohol emulsions at all tested conditions, and on the GE at the higher speed and load combinations. However, the GE did not perform well on the alcohol emulsions at low speed and load conditions, generating high smoke levels and low thermal efficiencies.

Water/Diesel Fuel Emulsions

Small reductions in brake specific fuel consumption (BSFC) and smoke levels can be attained through emulsification of water into diesel fuel. The BSFC reductions were on the order of 0.5 percent at rated speed and load of both the 12-cylinder EMD and GE engines, which is the level of repeatability of BSFC measurements during these tests. The improvements were of greater magnitude at the low speed/load conditions of the EMD, reaching a maximum of 2 percent BSFC reduction. The converse is true on the GE where BSFC increased above DF-2 levels in the lower speed and load operating realm. Smoke reductions occurred at all tested conditions.

No. 6/No. 2D Blends

No. 6 fuel oils can be blended with No. 2 diesel fuel to make a product acceptable for use in medium-speed diesel engines. No. 6 fuel oil properties vary widely, and a very good quality No. 6 will be needed to prevent filtration and deposit problems and permit a significant percentage to be blended with diesel fuel. A maximum of 18 percent volume No. 6 was tested on this program.

Low speed/load conditions, particularly idle, will most likely limit the amount of No. 6 that can be consumed. A continuous 48-hour idle test on the 12-cylinder EMD revealed that carbon deposits and unburned fuel are likely to accumulate in the exhaust system. Experiences of several railroads indicate that exhaust system fires can occur, causing turbocharger destruction. Reductions in thermal efficiency may occur at high No. 6 concentrations.

Long-Term Engine Wear, Deposits, and Durability

The AFFMSDE program has compiled an extensive data base on the effects of alternative fuels on engine performance and combustion characteristics. However, the data base is weak in the areas of exhaust emissions, wear, deposits, and durability. These areas are essential to the evaluation of an alternative fuel type. Emphasis should be placed on these areas in future investigations.

3. RECOMMENDATIONS

1. Up to this time, primary emphasis, both from technical and economical points of view, has been on the use of No. 6 fuel oils as the blend component with No. 2 diesel fuel for heavy fuel blends. However, other petroleum products are technically feasible for blending with DF-2 and may result in a blend with a lower cost per gallon than DF-2. Such fuels include other residual fuels such as No. 4 and No. 5, refinery stocks, and lubricating oils. Study the technical and economical aspects of such blends.

2. Gather information on the effects of alternative fuels on engine wear, deposits, and durability. Such effects are relatively long-term, requiring extensive engine operation for a proper evaluation. Such operation is usually economically feasible only in actual field operation. However, a preliminary assessment of the wear, deposits, and durability characteristics of an alternative fuel should be made in a laboratory engine before it is placed in field testing. Conduct a laboratory wear and deposit test of sufficient length to identify problems that are likely to arise with an alternative fuel before field testing this fuel.

3. Determine the maximum fuel viscosity that the full-size laboratory engines can tolerate as limited by engine performance and combustion characteristics. The engine fuel supply systems will need to be modified to overcome the limitations identified in this report. The combustion limited viscosity will be an area of concern when considering heavy blended fuels. These fuels will likely be of high viscosity and be used on engines with fuel systems specifically designed for their needs.

4. Study the effects of various alternative fuels on injection spray characteristics. The AFFMSDE program has encountered several fuels, particularly of higher viscosity and density, whose degraded engine performance was attributable to alterations in injection characteristics. The heavy blended fuels fall in this category. An assessment of the effects of fuels on spray penetration and droplet size is needed.

5. The amount of a No. 6 fuel oil that can be blended with No. 2 diesel fuel, and likewise the cost savings, are limited by the fuel tolerance capabilities of the medium-

speed diesel engines. If these tolerance limits could be extended, significantly higher portions of No. 6 fuel could be consumed, thereby reducing the fuel blend cost. Study means to permit engine operation on the maximum possible amount of the low cost blend component. Such techniques might include the use of fuel heating, fuel centrifuging, staged injection, and water emulsions.

6. Assess the feasibility of constructing a single injection system capable of reproducing the staged injection characteristics of the two separate injection systems used during the two-cylinder engine experiments. This system should be suitable for direct replacement of existing fuel injection systems on field engines. Such a system would greatly expand the cetane number limits without requiring a major modification to the engine.

7. Study means to improve the sensitivity of the spectrographic oil sampling technique for short-term wear analyses. A short-term technique is needed to define the wear characteristics of alternative fuels before they undergo extensive laboratory or field testing. Also, study other short-term wear techniques to determine if a method with high sensitivity is available.

8. Monitor the results of the USDA vegetable oil study being conducted at SwRI. This program will determine the effects of refining on vegetable oil properties and, subsequently, on the performance of a small laboratory diesel engine. The effects of the vegetable oils on crankcase lubricating oils will also be studied. Further testing of vegetable oils on the AFFMSDE program should not be undertaken until the results of the USDA program have been examined.

9. Slurry fuels should not be considered for further evaluation in this program. While it is technically feasible to consume these fuels, the developmental work needed to achieve acceptable engine performance is considerable.

10. Examine the safety and handling aspects of alternative fuels. Background information necessary for this study would include chemical, physical, and physiological characterizations of candidate fuels and data on current handling and safety practices

in the field. All of the alternative fuels tested in the program to date and those considered for evaluation in the near future should be included.

11. Organize a guidebook with step-by-step procedures for blending and use of emergency fuels to extend standard diesel fuel during fuel shortages. These fuels must produce acceptable engine performance with minimum sacrifice of durability and emissions. The majority of the candidate alternative fuels considered in this and other programs are not acceptable replacements for No. 2 diesel fuel at this time, but would be valuable resources in emergencies. Alcohols, solvents, jet fuels, heating oils, residual fuels, crude oil, and vegetable oils are potential candidates. Data on hand are not sufficiently extensive to formulate the guidebook; additional engine and chemical laboratory testing is needed.

12. Examine gaseous fuels for their potential as alternative fuels for medium-speed diesel engines. This class of fuels has not yet been examined in this program. The technology for converting engines to gaseous fuel operation already exists. Methods for storage, handling, and consumption of each type of gaseous fuel should be considered. The problems associated with implementation of gaseous fuels should be determined.

13. Perform an economic analysis of the alternative fuels studied to date as well as those considered for the near future. This analysis should include fuel costs, equipment conversion, maintenance, durability, fuel availability, and operating costs. A ranking of alternative fuels could then be developed. Develop a second ranking considering these same fuels but in an emergency fuel scenario. In this case, fuel availability and the ease with which an engine and/or fuel system can be converted to handle the fuel are of primary concern, and economics are a lower priority.

14. Update the Alternative Fuels Program Management Plan originally developed by E:F Technology, Inc. to reflect the developments and changes that have occurred since its last revision. This plan is needed to assure that the program reaches its goal in a timely and orderly fashion.

4. INTRODUCTION

4.1 BACKGROUND

The work covered in this report constitutes the third research phase of an ongoing alternative fuels investigation that began at SwRI in August 1978. The program is a multi-year research, development and demonstration effort to investigate the use of alternative fuels in medium-speed diesel engines. The program roughly follows a six-year plan developed by E:F Technology Associates, Inc., during the first year of this project.(1)

The cooperative "Alternative Fuels for Medium-Speed Diesel Engines" (AFFMSDE) program began under the sponsorship of the U.S. Department of Energy. During the first year of operation, significant funding was also obtained from the Federal Railroad Administration of the U.S. Department of Transportation. The Association of American Railroads (AAR) has been involved in program planning and review functions since 1978. The AAR contributed, through its member companies, two full-sized locomotive diesel engines that were installed at SwRI in 1980. The AAR has also provided funding since 1981. Government funding will be discontinued at the end of Phase III, at which time the AAR will assume responsibility for the AFFMSDE program.

Medium-speed diesel engines, which are characterized by a maximum speed of between 800 and 1200 rpm, are used in several types of essential transport and power supply functions. The leading users of these engines are the railroads, followed by marine propulsion systems and stationery power generation facilities. The original impetus behind this program was the dependency of these engines and their important functions on an adequate supply of high-quality diesel fuel, usually of No. 2 specifications. The supply and pricing of such fuel is largely under the influence of foreign oil producers. The fact that the vital supply of No. 2 fuel can be curtailed became evident during 1974 and 1979, clearly indicating that industry is vulnerable to this threat. Therefore, alternative fuels must be found as insurance against curtailment or shutdown of the essential functions performed by this class of engines.

In addition, the price increases of No. 2 fuel which have occurred since 1974 have placed a severe burden upon the transportation and shipping operations in the United States. In the case of the railroads, which consumed approximately 3.7 billion gallons of No. 2 diesel fuel in 1982, high fuel prices now result in fuel being a large percentage of rail operation costs. It is therefore imperative that fuels be found that are potentially of lower cost relative to DF-2. Much of the work covered in this report, along with most of the tasks planned for 1983, are directed toward the investigation of potentially lower cost fuels.

Thus, the program involves investigation of fuels potentially available in significant quantities to meet usage requirements, but which otherwise fall into two general categories: those that may serve as alternatives to petroleum distillates in order to ensure continued engine operation in a fuel-shortage, and those that may be available at lower cost (relative to DF-2). It should be noted that fuels in these two classifications are often very different from one another, not only in their technical (chemical and physical) properties but also in the manner in which they would be implemented for use with medium-speed diesel engines. For instance, alternative fuels in the first category are not selected based on cost. Fuel availability and ease with which engine and/or fuel system can be converted to handle the fuel are of primary concern. The fuels that will be available in a fuel shortage may be of poor quality and require significant engine or fuel system modification. On the other hand, fuels in the second category are primarily selected considering factors of cost and availability in the very near term, if not immediately. These fuels would be used in essentially unmodified engines to minimize conversion costs and would require a minimum of technical problems to be solved before their implementation.

The program scope of work thus encompasses many fuels of great diversity. This fact will assist in understanding the various technical phases of the program. These are discussed in the following paragraphs.

The initial (research) phase of the program involves the laboratory investigation of the operating characteristics of medium-speed diesel engines using selected alternative fuels. Engine performance, emissions, and durability are being studied in this phase. The results will define the fuel tolerance envelope of the engine and will provide basic information about any hardware modifications which are required for satisfactory operation with these fuels.

The intermediate (development) phase of the program is concerned with bringing the engine hardware and related equipment from the research stage to a state of more advanced design which will permit extended operation of the full-sized locomotive engines under simulated locomotive duty cycle conditions in the laboratory. Not every fuel investigated in the research phase will be carried over into the development phase. The goal of the development work will be to solve the salient technical problems of engine operation with candidate alternative fuels in order to obtain acceptable levels of performance, durability, and emissions. Engineering problems associated with the operation of the engines on these fuels will be defined and solved in this phase.

The last (field test) phase of the program will involve long-term testing of fuels in locomotives in revenue service operation. This will provide practical experience with alternative fuels and define long-term effects which cannot be determined in the laboratory. Because field testing is complicated and expensive, not every fuel which is investigated in the development phase will be used in the field tests.

Almost all work performed to date in the program has been done in the research phase, and two previous reports have been issued which cover these accomplishments.(2,3) The first report dealt with the use of off-specification diesel fuels and two non-diesel fuels. Off-specification diesel fuels are defined as fuels with one or more properties that do not lie in the currently accepted range of No. 2 fuel specifications. Tests were conducted to assess the effects of diesel fuel cetane number, viscosity, and boiling (distillation) range on the performance and emissions of a two-cylinder laboratory EMD engine. The non-diesel fuels evaluated were methanol and a simulated coal-derived fuel. They were tested in a dual-fuel mode using pilot diesel fuel injection to initiate combustion of the main fuel. The same laboratory test engine was employed. The second report covered work involving hybrid fuels (i.e., mixtures of two dissimilar fuels) as well as other off-specification diesel fuels and non-diesel fuels. An emulsion of alcohol (methanol or ethanol) in No. 2 diesel fuel is an example of a hybrid fuel. Several emulsions were tested in both stabilized and unstabilized forms;

that is, with and without a chemical stabilizer being used. Off-specification diesel fuel experiments were a continuation of work presented in the first report. In this follow-up work, attempts were made to improve engine performance while operating on very low cetane number diesel fuel and to assess starting problems for an engine operating on such fuels. A simulated No. 3 diesel fuel is an example of an off-specification fuel. Non-diesel fuels tested included straight (neat) alcohols as well as two synthetic fuels, one a coal-derived liquid and the other a shale oil product. The two full-sized locomotive engines were installed during the course of this work and were the principle test tools for the off-specification diesel fuels.

The technical tasks covered in this third report in the series are specified below:

- Test of vegetable oil/DF-2 blends, plus neat (100 percent) vegetable oil, all conducted with the two-cylinder EMD laboratory engine. These tests were also conducted using the 12-cylinder engine after successful two-cylinder engine testing.

- Carbon black/DF-2 slurries were evaluated in bench tests of fuel injection equipment and with two-cylinder EMD engine tests.

- A study was undertaken to develop a method to measure cylinder liner/piston ring wear over a short period of operating time by means of spectrographic analysis of oil samples taken directly from the cylinder liner wall (2-567 engine only).

- A chemical laboratory study was conducted for No. 6 oil stocks and the resulting No. 6/DF-2 blends in order to obtain data in preparation for laboratory engine tests with typical blends.

- Testing of alcohol/DF-2 emulsions was conducted using both full-sized engines.

- An engine performance evaluation was conducted for water-in-diesel fuel emulsions also using the 12-cylinder engines.

- A typical No. 6/DF-2 blend was evaluated in the full-sized engines.

4.2 PROGRAM MANAGEMENT ORGANIZATION

Virtually from the program inception until the present time the program management structure was influenced by the fact that SwRI was operating under separate contracts from DOE/FRA and AAR. The management organization is illustrated in Figure 4.1. The AAR Alternative Fuels Steering Committee is comprised of representatives of the government, the AAR, the engine manufacturers (EMD, GE and Bombardier), and a number of railroads. Thus, although SwRI has been responsible to the Government and the AAR under the terms of their specific contract, overall direction of the program is in the hands of the Steering Committee. The Steering Committee meets periodically to review progress of the program and to discuss specific technical problems and options, and a consensus is normally reached which provides the directive for SwRI. Three to four meetings per year are held.

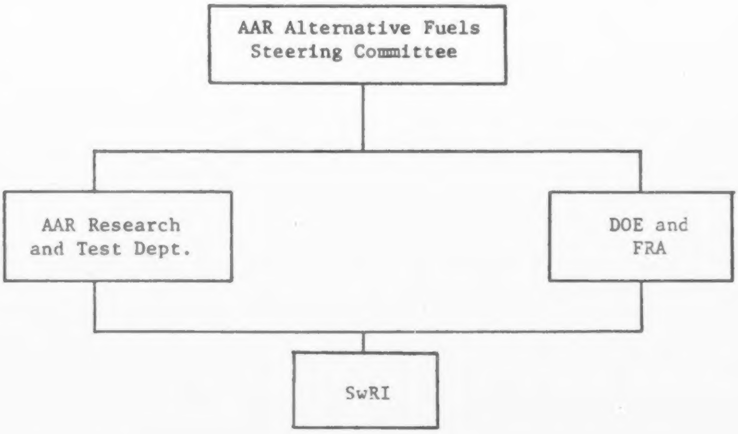

AAR Alternative Fuels Steering Committee
AAR Research and Test Dept.
DOE and FRA
SwRI

FIGURE 4.1 PROGRAM MANAGEMENT ORGANIZATION

4.3 OBJECTIVES

The phase of the program reported here had as objectives the specific technical tasks that were presented at the end of Section 4.1. However, a broader objective was to begin to emphasize the need to investigate fuels of potentially lower cost that would be available for use in the very near term. This change was in response to the railroads' increasing concern over fuel cost as opposed to fuel availability, and reflects the political and economic factors which have existed in a more-or-less stable state over the last two years.

4.4 TECHNICAL APPROACH

The approach used in the alternative fuels investigation is based around the three laboratory medium-speed diesel engines at SwRI. Candidate fuels selected for testing covered a broad range of fuel types and properties. This broad-based approach is designed to provide laboratory-derived information for a wide range of fuels and, therefore, allows to some extent for the uncertainty in predicting future fuel availability and cost. Those fuels selected for initial testing are evaluated in the two-cylinder EMD 567B engine. If the fuel produces acceptable performance, combustion, and emissions characteristics, it then becomes a candidate for testing in the two full-sized locomotive engines under simulated rail operating conditions. The two-cylinder engine is thus a screening tool which permits rapid and relatively inexpensive evaluation of a fuel before advanced verification testing in the large engines.

Fuels that are very close to No. 2 diesel fuel in their specifications are tested with the engines in standard configurations, i.e., without modification. These tests define the limitations and problems for use of each candidate fuel in existing medium-speed diesel engines. In the case of off-specification diesel fuels, a single fuel property is varied as independently of other properties as possible by blending selected components together, often with a No. 2 fuel base. The tolerance limits of the 2-567 engine for fuel cetane number, viscosity, and boiling range were determined by this method in Phase I, and cetane and viscosity limits were investigated with the full-sized engines in Phase II.

A similar approach has been taken to evaluate hybrid fuels such as alcohol/diesel fuel emulsions in the two-cylinder engine. The volume of alcohol in the emulsion was systematically increased until the knock limit of the engine was encountered.

Non-diesel fuels such as neat alcohols and coal-derived liquid fuel required the use of a dual-fuel (pilot injection) system to overcome the self-ignition problems of these low cetane number fuels. This is one of the few instances where an extensive engine modification was performed, in this case with the two-cylinder EMD, to add the pilot injection system. Injection parameters and fuel rates for both pilot and main fuels were varied to achieve maximum alternative fuel usage with acceptable engine performance and minimum combustion problems.

Due primarily to the expense involved, gaseous and particulate exhaust emissions data have not been obtained for each fuel evaluated. Most emissions measurements were made with selected fuels tested in the two-cylinder engine.

5. EXPERIMENTAL APPARATUS AND TECHNIQUES

5.1 DESCRIPTION OF TEST ENGINES

A total of three test engines were used in this study. The first was the two-cylinder version of the Electro-Motive Division (EMD) model 567B engine (Figure 5.1). This was a limited production engine that was intended for research use only. The 567 series engines were produced in 8-, 12-, and 16-cylinder configurations. It is a blower-scavenged, two-stroke cycle engine with a displacement of 567 cubic inches per cylinder. Pertinent engine specifications are shown in Table 5.1. Full-size 567 engines are used in a variety of configurations, depending on application. The version most representative of in-service engines (using 16:1 compression ratio pistons, 20 port cylinder liners, and fuel injectors calibrated for the medium air flow range) was chosen as the test configuration(4).

The two additional test engines, which were installed at SwRI during the course of this study (late 1979), represent two of the most commonly used medium-speed diesel engines in the United States. They are the 12-cylinder versions of the EMD 645 E3 and the GE 7FDL engines (Figure 5.2). Both engines are turbocharged, each generating about 2500 brake horsepower at the flywheel. The EMD is a two-stroke cycle engine, while the GE operates on the four-stroke cycle. The EMD is loaded by a DC generator, and the GE by a DC rectified alternator. The DC power output is absorbed by two Alco locomotive load grids equipped with cooling fans for heat dissipation.

The cooling system shared by the two 12-cylinder diesel engines is a modified version of the standard locomotive system. Six General Electric locomotive radiators are mounted in a specially constructed stand. Cooling air is forced through these radiators by a constant speed, variable pitch turbine fan (Figure 5.2). The fan pitch is thermostatically controlled to maintain a constant coolant temperature. In addition, each engine is equipped with its own thermostat to minimize warm-up time and maintain a constant coolant temperature during low power operation. The cooling and power absorption systems can handle only one engine at a time.

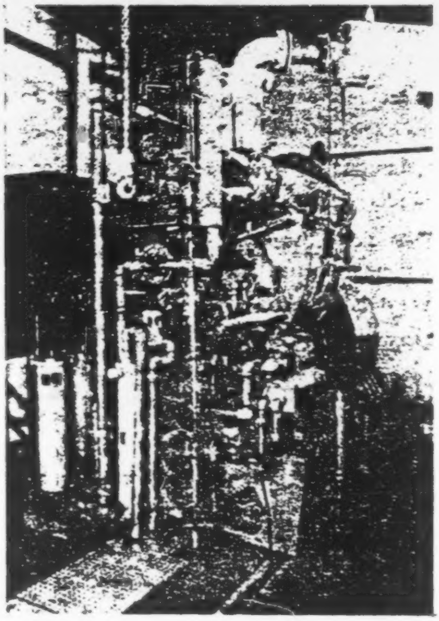


FIGURE 5.1 TWO-CYLINDER EMD 567B TEST ENGINE

Diesel fuel for the two-cylinder engine was stored in an underground tank. The majority of the test fuel blends were made in 55 gallon batches and stored in drums. The blends were pumped directly from the drums to the engine during tests. Five underground fuel tanks, ranging in size from 1000 to 10,000 gallon capacities, supplied the 12-cylinder test engines through an interconnected patch system. Fuel could be pumped to or from any combination of tanks for mixing or from any tank to the test engines.

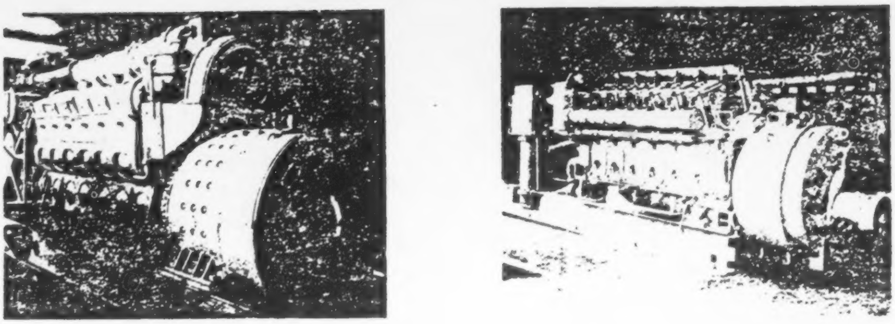


FIGURE 5.2A 12-CYLINDER EMD 645 E3 (left) and GE 7FDL (right) ENGINES

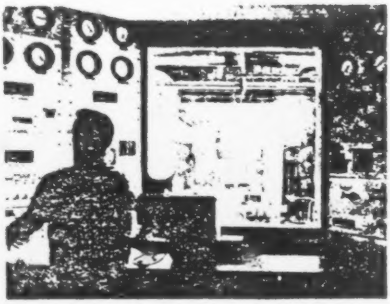


FIGURE 5.2B CONTROL ROOM FOR 12-CYLINDER ENGINE OPERATION

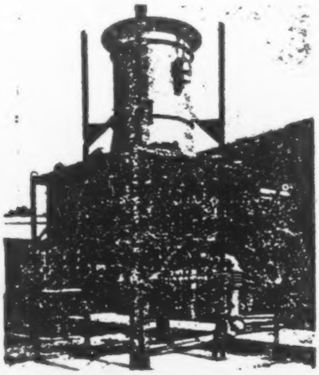


FIGURE 5.2C 12-CYLINDER ENGINE COOLING TOWER

Table 5.1. Engine Specifications

	EMD 2-567B	EMD 12-645 E3B	GE 12-7FDL
Type	2-stroke diesel, Roots-blown	2-stroke diesel, turbocharged	4-stroke diesel, turbocharged
Bore (in.)	8.5	9-1/16	9
Stroke (in.)	10	10	10.5
Displacement (cu. in/cyl.)	567	645	668
No. of Cylinders	2	12	12
Compression Ratio	16	14.5	12.7
Injection System	Unit Injector	Unit Injector	Jerk pump/nozzle
Rated Brake Horsepower (at flywheel)	215	2500	2500
Rated Speed (rpm)	835	900	1050

5.2 ENGINE TEST CYCLES

All three engines were operated at conditions that simulated the "notched" operation of their respective line-haul locomotives. Locomotive engines operate at only specified speed/power combinations defined by a set of throttle positions or "notches". Since power output and speed of each notch position are constant, the fuel consumption rate is also constant and can be defined for each position. EMD and GE engines in line-haul service operate in eight power producing notches, in addition to idle. Some of the engines are also equipped with low idle, and some with dynamic brake positions, but these were not tested on this program. To facilitate fuels testing, the notch schedules were redefined in terms of speed/fuel consumption rate combinations (see notch schedules presented in Table 5.2). Notch 8 of each schedule represents rated speed and load of the engine; all other positions represent part load conditions. Fuel rates for the two-cylinder 567 EMD research engine were taken as 1/8 the typical values for the 16-cylinder 567C with 16:1 compression ratio pistons; therefore, the 2-567B was operated throughout these tests as a C series engine. Fuel consumption values for the GE engine were determined through engine tests during which the fuel rates were observed at the speed/load combinations recommended by GE(5). Fuel rates used for the 12-cylinder EMD tests were taken from fuel consumption data provided by EMD(6).

Table 5.2. Engine Notch Schedules

	2-Cylinder EMD		12-Cylinder EMD		12-Cylinder GE	
Notch Position	Engine rpm	Baseline No. 2 Diesel Fuel Rate (lb/hr)	Engine rpm	Baseline No. 2 Diesel Fuel Rate (lb/hr)	Engine rpm	Baseline No. 2 Diesel Fuel Rate (lb/hr)
Idle	285	Observed	315	Observed	450	Observed
1	285	8.0	315	55.7	450	51.7
2	344	11.8	387	163.0	536	104.8
3	424	21.2	488	227.3	707	205.2
4	515	32.5	565	331.4	765	320.4
5	584	45.7	650	410.4	879	454.9
6	675	60.0	736	554.0	879	590.2
7	755	75.6	820	749.0	964	697.2
8	835	93.8	904	889.0	1050	862.1

Unlike locomotive engines, each test engine was equipped with a pneumatic governor that permitted infinite variations of both speed and load. However, during testing, engine operation was restricted to the engine speeds and fuel consumption rates corresponding to the notch schedules presented in Table 5.2.

A wide variety of fuels have been tested in this program. Due to the properties of the fuel, it was sometimes impractical to test according to the specified mass fuel consumption rate shown on the notch schedule. In these cases, the schedule was reconfigured to reflect total fuel heat energy content or a constant horsepower output. These alternative schedule standards were used when they offered a more realistic operating schedule or provided a better correlation to performance data acquired with other fuels, or if there was no other choice given because of the properties of that fuel. An explanation of these alternative test standards follows:

- **Constant mass flow rate** — The engine fuel mass consumption was set to equal that specified in the notch schedule. Mass flow rates were used when the fuel possessed density and heat values nearly identical to those of No. 2 diesel fuel. Most petroleum derived distillate products, such as low cetane number blended fuels, met this criteria. Equivalent mass flow rate was the preferred and most frequently used test standard.

- **Constant horsepower output** — When fuel density or heat content differed significantly from that of DF-2, operating at baseline fuel mass flow rates would have caused significant changes in power output. For example, the higher heating value of sunflower oil was 13 percent below that of diesel fuel. Testing at the same mass fuel consumption as diesel fuel would have resulted in a major power loss. A more realistic comparison of the test fuel to diesel fuel would result from testing at power outputs equal to baseline values.

- **Equal BTU input** - Hybrid fuels (mixtures of two different fuel types) and other fuels tested in the dual-fuel mode were supplied to the engine on an equivalent fuel heat energy input basis. The sum of the heat energy supplied by each fuel source was set to equal that of the baseline diesel fuel at the same notch position. When operating the engine on two different fuel types, this approach was the most realistic and practical.

The following daily test procedure was used for all test engines with a single exception. The engines were started, warmed up, and performance was checked on DF-2 at one of the notch positions, usually Notch 8, prior to alternative fuels testing. Engine operation was then transferred to the test fuel while running. After allowing sufficient time for the engine to completely consume any diesel fuel remaining in the fuel system, data points were recorded. At the completion of each test day, the engine was switched back to operation on DF-2 and run for sufficient time to thoroughly purge the system of the test fuel. The 48-hour idle test (see Section 8.5) was the exception; the engine was stopped on the test fuel so that the carbon deposits would not be disturbed. Two replicate tests were usually recorded per fuel to establish satisfactory data confidence, except where test fuels were in short supply or where poor data agreement required additional data.

The test engines remained in their standard configuration throughout these tests except where alterations are specifically noted. The engines were maintained according to the manufacturers' recommended procedures.

Performance data were corrected to standard ambient conditions in all cases. Factors defined by EMD were applied to the EMD engines to correct performance to 60°F and 29.90 in-Hg. GE engine performance was corrected according to GE recommended factors to 60°F and 28.86 in-Hg barometric pressure.

5.3 ENGINE INSTRUMENTATION

All three test engines were completely instrumented to monitor engine speed, power output, and pressures and temperatures throughout the lubricating, cooling, intake, and exhaust systems. In addition, instrumentation was added to record start and end of fuel injection. This was accomplished on the EMD engines by mounting strain gages on the unit injector rocker arm, and on the GE by mounting a piezoelectric pressure transducer in the high pressure injection line. Smoke density was measured using the Bosch method. Flo-tron linear mass flowmeters provided continuous fuel mass flow rate measurements.

The 12-cylinder engines were connected to a low-speed computer data acquisition system in September 1982. The computer system monitored generator or alternator voltage and amperage output and the Flo-tron voltage signal. These three signals were recorded once every three seconds for forty readings, totaling a two minute period for data sampling. The forty readings were averaged and the power output, thermal efficiency and brake specific fuel consumption were calculated based on these averages. The averaging process nullified oscillations in power output and fuel consumption rate, providing more precise specific fuel consumption data than values read manually. Data for the water/DF-2 emulsions, sunflower oil, and No. 6 blend series were acquired by the computer system.

Fuel temperature was measured ahead of the primary fuel filters. Fuel was heated or cooled as necessary through heat exchangers to maintain a 100 ± 5°F temperature, with one exception. Fuel temperature was varied during the high viscosity tests (Section 8.1) to alter fuel viscosity. A special heating system was added for this purpose, producing fuel temperatures from 80 to 165°F at the engine fuel filters.

A piezoelectric pressure transducer was mounted in one cylinder head of each engine to provide a continuous cylinder pressure measurement. The pressure transducer was mounted in a specially drilled passage in the two-cylinder EMD engine head and the GE power assembly. The transducer for the 12-cylinder EMD engine was mounted in a pressure relief passage. A fixture that replaced the blow-down valve assembly positioned the transducer as close to the combustion chamber as possible without modifying the head, and cooled the transducer using tap water. Cylinder pressure, the injection event (fuel pressure or rocker arm strain), crankshaft position, and in the case of the two-cylinder engine, the injection pressure in the secondary injection system, were displayed on an oscilloscope.

The cylinder pressure and rocker arm strain signals were recorded by a high-speed data acquisition system for heat release analysis during two-cylinder EMD carbon slurry tests. The signals were read once every one-half crank angle degree for 100 consecutive cycles. The average and standard deviation of the pressure was then calculated for each of the 720 increments. The amount of fuel energy (heat) released from one crank angle increment to the next was calculated based on the change in cylinder pressure and volume (piston position).

6. ENGINEERING STUDIES

Three engineering studies were initiated during the course of the program. These studies differ from the later tasks described in this report because none of the three involved any engine testing or evaluation. They were performed in preparation for future laboratory and field engine testing. The three studies were the specification of a minimum quality residual blend, the development of an integrated test planning guideline for laboratory and field alternative fuels studies, and the compilation of a field test manual for in-service locomotive testing of alternative fuels. Each of these studies was a "stand alone" task whose results are described in depth in individual reports. The following sections provide only a brief description of their purpose, objectives, and results. References are provided for readers who want further information.

6.1 MINIMUM QUALITY RESIDUAL FUEL BLEND

This study explored the blending of No. 6 residual fuel with railroad diesel fuel as a potential cost saving method (7). No. 6 fuel oils are attractive because of availability and price, but they are not suitable for direct use in medium-speed diesel engines. However, blending No. 6 with diesel fuel is feasible. The alternative fuels program has demonstrated that medium-speed diesel engines can tolerate fuel properties well beyond the No. 2 diesel specification. Therefore, the limits of existing diesel fuel specifications can be extended to take advantage of the engine fuel tolerance, allowing a reasonable amount of No. 6 fuel oil in the blend.

Properties of No. 6 fuel oil vary widely. The ASTM specification for these oils is not very restrictive. Refiners are free to change composition as long as the final product meets the specification. Compositions are likely to vary since each refinery uses different processing equipment for different product objectives. Shifting crude quality and seasonal changes in product demand also contribute to the variations.

No. 6 fuel oils contain more sulfur and carbon residue than diesel fuel, and may contain other contaminants such as metals and catalyst fines. An excess of various contaminants could cause operational problems or engine damage. There are also other properties important for diesel engine operation, such as cetane number and distillation range, that are not normally measured and for which little data is available. The study examined each of these areas to define the limitations to No. 6 fuel oil use.

The following steps were used in the study:

- Determine the ranges of fuel properties available from surveys of No. 6 fuel oils and railroad diesel fuels (a poor quality DF-2) in the U.S.
- Obtain representative samples of a variety of No. 6 fuel oils and railroad diesel fuels.
- Generate a blending guideline from known or estimated engine fuel property tolerance limits.
- Make blends using the maximum amount of No. 6 fuel oil permitted by the guideline. Obtain complete blend analyses and identify problem areas.

The objective was to achieve maximum utilization to minimize fuel cost while staying within the fuel tolerance limits of the engines. When tolerance limits were uncertain, conservative values were adopted.

Survey data compiled by the Department of Energy, Bartlesville Technology Center(8), showed that No. 6 fuel oil properties vary widely (see Table 6.1). Eight samples of No. 6 fuel oils obtained from four suppliers confirmed that wide variations in properties of No. 6 are not uncommon. Therefore, analyses of candidate No. 6 fuel oils were a necessary first step before blending. It would not be advisable to use a predetermined amount of No. 6 fuel oil, such as a constant volume proportion, in the blend. Rather, the actual No. 6 fuel oil to be consumed should be analyzed, then the blend content estimated to keep blend properties within engine fuel property tolerance limits.

Table 6.1 1981 Property Ranges of No. 6 Fuel Oils

	Minimum	U. S. Average	Maximum
Gravity, °API	3.3	12.6	20.1
Flash Point, °F	152	203	256
Viscosity,			
cSt @ 100°F	34	950	1900
cSt @ 122°F	15	180	327
Pour Point.°F	10	43	120
Sulfur, Wt %	0.21	1.62	3.60
Carbon Residue, Wt % on oil	0.80	7.44	15.90

A guideline was developed for No. 6/DF-2 blend quality. The guideline is presented in Table 6.2. A constraint placed on the development of this guideline was that the blended fuel be acceptable for use in an unmodified locomotive engine. The values of the fuel properties selected were based on data available from engine tests conducted during the alternative fuels program, published recommendations from engine manufacturers, and, where no information was available, from conservative judgments. The guideline contains several tests not normally performed on diesel fuel that became important when No. 6 fuel oils were used as a component.

The guideline should not be considered a specification since it was generated from available information on engine tolerance levels. That information was deficient in long-term effects on engine wear or deposits. The guideline is a recommendation for property limits that should be used during initial laboratory and field experiments. Caution should be exercised in its use, and revisions should be made on the basis of engine experience.

Trial blends were prepared using five No. 6 fuel oil samples to the maximum No. 6 concentration allowable by the blend guideline. The following potential problems were identified as a result:

- Filtration of some fuels may be prevented by asphaltenes that coat filter surfaces. Presence of these compounds is indicated by tests for pentane insolubles, carbon residue, or compatibility.

Table 6.2 Proposed Guideline for Blends of No. 6 and Railroad Diesel Fuel

Property	Proposed Guidelines (1)
Gravity, °API	N.S.
Distillation, °F	
90% Recovered	680
End Point	N.S.
Recovery	N.S.
Cetane Number	35 min
Cetane Index	35 min
Viscosity,	
cSt @ 100°F (37.8°C)	16.5
cSt @ 104°F (40°C)	15
Flash Point, °F	N.S.
Pour Point, °F	N.S.
Ash, Wt. %	0.02
Carbon Residue,	
Wt % on oil, Ramsbtm.	1.5
Wt % on oil, Conradson	2.0
Sulfur, Wt. %	1.5
Corrosion, Cu Strip	3.0
Total Water and Sediment, Vol. %	0.1
Particulates, mg/100 ml	N.S.
Pentane Insolubles, Wt. %	1.0
Organic Chlorides	N.S.
Metals, Wt. ppm	
Vanadium	30
Nickel	10
Sodium + Potassium	10
Aluminum	5
Silicon	N.S.
Calcium	N.S.
Lead	N.S.
Catalyst Fines	N.S.
Compatibility	2
Accelerated Stability	N.S.

NOTES: (1) All maximum unless noted otherwise
N.S. Not specified

- Metals content is a probable limitation on the No. 6 fuel oil content of blends.

- Aluminum content may be used as an indicator of cracking catalyst fines, which are predominately alumina-silica compounds, but high sensitivity is required to detect the low concentrations that commonly occur. Filtration tests may be used to detect catalyst fines, but organic sediment may obscure the results.

A final precaution: the guideline approaches known fuel tolerance limits of common medium-speed diesel engines, and the long-term effects are unknown. Although conservative fuel property values were chosen for this study, they should be used with due consideration of the type of service required of the engine. For example, if extensive idling is expected, a clean No. 2 diesel fuel would be preferred. A residual blend would be recommended only where a high power condition is used most of the time.

6.2 INTEGRATED TEST PLANNING (ITP) GUIDELINES

The objective of the Integrated Test Planning (ITP) Guidelines is to document an integrated approach to research, development and operational evaluation planning that will make the best use of each type of operating environment, i.e., stationary engine dynamometer systems and rail or marine motive power unit operation in revenue service.(9) The ITP Guidelines provide:

- A background discussion of the state-of-the-art in alternative fuels and energy conserving devices, technologies and presently identifiable areas of technological, cost, demand, institutional, and external uncertainties.

- A discussion of a range of considerations that will affect the sequence of the approach to research, development, and operational evaluation of various alternate fuel types/forms and various energy conserving technologies.

- A discussion of preliminary supporting investigation requirements.

- A categorization of operational objectives for research, development, and evaluation of operations in stationary and rail and marine motive power systems.

- A review of the capabilities and limitations of the SwRI MSDE Laboratory.

- A review of the capabilities and limitations of testing functions in rail and marine motive power unit systems in operating environments.

- A comparison of the capabilities and limitations of the two R&D and operational environment approaches (laboratory and field testing) to identified requirements.

- Guidelines for Integrated Test Planning for MSDE Laboratory and operational motive power unit and vessel operations.

Different types of investigations are appropriate to different types of environments. Some types of investigations can best be, or only be, carried out -- practically and thoroughly -- in one type of environment.

Equipment owners and fuels and lubricants manufacturers must often conduct research and development in medium-speed diesel engine (MSDE) related systems using full-scale motive power equipment operating in revenue service. This approach has often been the only economically feasible alternative to the expense of constructing full-scale MSDE dynamometer systems that are used once or infrequently to support a specific research or development project. But carrying out research and development in an operating environment is generally acknowledged to be a most difficult, costly, and restrictive approach. Generally, only railroad motive power unit manufacturers can justify financially the maintenance of a full-scale, stationary engine/dynamometer research capability.

Construction of the Medium-Speed Diesel Engine Laboratory at Southwest Research Institute (SwRI) offers an opportunity for an integrated approach to research, development, and operational demonstration of alternative fuel and energy conserving systems for rail and marine motive power equipment. This opportunity is provided in an independent, industrial research environment with a non-profit organizational setting fully supported by related laboratory and specialist capabilities.

The MSDE laboratory at SwRI offers three fully instrumented, medium-speed diesel engine research systems:

- An EMD 2-567B, two-cylinder, two-stroke, blower scavenged test engine system;
- An EMD 645 E3, twelve-cylinder, two-stroke, turbocharged test engine system;
- A GE 7FDL, twelve-cylinder, four-stroke, turbocharged test engine system.

These research engine systems, and the supporting specialist staff and laboratory systems, can meet the requirements of research and development programs in alternative fuel and energy conserving systems. However, laboratory research and development cannot provide demonstration of long-term reliability, maintainability, and the economics of system operation in rail line-haul or marine operating scenarios. Evaluations of these aspects should be carried out with full-scale equipment in a real operating environment. This type of investigation requires full-scale motive power equipment using alternative fuel and energy conserving systems in day-to-day operations, and the involvement of operational company personnel and support systems.

Wear measurement in basic engine systems is an additional field of investigation also uniquely appropriate to evaluation in an operating environment. At present, there is no wear measurement system that can provide reliable data in short test times. Long duration, continuous operation (to several thousand hours) is generally economically impractical in stationary engine systems simply because of the high cost of fuel required to conduct such testing. The economic alternative, in the absence of reliable, short-duration wear measurement techniques, is to go to revenue service to offset the fuel cost component of such testing.

6.3 FIELD TEST MANUAL

The purpose of this study was to assist in producing a guideline for conducting field tests of heavy blended fuels in railroad locomotives.(10) Field tests are the final step in the evaluation of a candidate alternative fuel following screening through laboratory performance evaluations and extended operation (500-1000 hour) testing. The outcome of the study will be the compilation of a manual by the AAR for use by railroad companies.

Field tests of candidate alternative fuels are an essential step in the evaluation procedure. The long-term effects of the fuel on engine wear, deposits, reliability, and availability cannot be simulated in a laboratory either realistically or economically. The service life of the medium-speed diesel engines is extremely long, making it difficult to operate an engine in a laboratory for sufficient time to generate appreciable deposits or wear. Field testing adds many "real life" variables that are not encountered in the laboratory, such as frequent changes in operating environment. Field testing also provides insight into fuel supply, handling, and storage, which ultimately affect the economics of the use of a fuel.

Railroad companies are experienced at conducting field tests. Test procedures for field evaluation of crankcase lubricating oils are well documented (11). However, no procedures exist for alternative fuels testing. The purposes of the field test manual are to ensure that proper engineering practices are followed, adequate data are acquired for an extensive evaluation, and the data are of good quality for a complete analysis. The manual attempts to standardize test procedures so that the results of different programs can be readily compared.

Included in the field test manual are criteria for selection of test fuels, and the design of a test appropriate for these fuels. Methods are described for proper preparation of the locomotive as well as for fuel storage and delivery systems. The manual recommends the type of operation to which the locomotives should be subjected and procedures to follow in conducting the tests to ensure that the locomotives are operated as specified. Analyses are also recommended for determining effects of the fuel on engine performance, wear, reliability, consumption rate, and ultimately operating and maintenance costs.

7. TEST RESULTS: TWO-CYLINDER EMD ENGINE EXPERIMENTS

This section documents data obtained from tests using the two-cylinder EMD 567B test engine. This limited production engine was constructed solely for research and testing applications. The two-cylinder engine is an extremely valuable tool that permits rapid and inexpensive evaluations of alternative fuels. Of course, this engine should not be compared with current production models because the power output per cylinder is a little over one-half that of the full-scale engines at SwRI. The results from the two-cylinder tests are intended for assessing the feasibility of using a particular fuel and should not be interpreted as pertaining to full-size engines. In this respect, the two-cylinder engine is considered a screening tool by which candidate fuels are first evaluated. Fuels that look promising are tested further in the 12-cylinder engines.

7.1 LOW CETANE NUMBER FUEL PERFORMANCE OPTIMIZATION

The Phase I low cetane number fuel tests revealed that the two-cylinder test engine could tolerate fuels with a cetane number as low as 30 before significant changes occurred. Below 30 cetane, the rate of pressure rise increased dramatically, causing audible knocking. Due to long ignition delay (the period of time between start of injection and start of combustion) of low cetane number fuel, a large volume of fuel was injected into the combustion chamber before start of combustion. When ignition occurred, this fuel burned very quickly and violently, producing a high rate of pressure rise.

Improving low cetane number fuel performance therefore requires speeding the ignition process to prevent fuel accumulation in the combustion chamber before the start of combustion. Ignition delay is composed of two periods; physical and chemical. The former is the time required to atomize, vaporize and disperse the fuel in the combustion chamber. The fuel must then undergo pre-flame chemical reactions, which constitute the chemical delay. If either of these two periods can be shortened, ignition delay and knocking will be reduced.

The physical delay depends on the injection characteristics and air swirl in the combustion chamber. The swirl characteristics of the two-cylinder test engine could be altered by modifying the cylinder liner air intake ports or combustion chamber geometry; however, such modifications are quite extensive and were beyond the scope of this program. This study assumes that the injection characteristics and swirl pattern have been optimized by the engine manufacturers in their research for minimum fuel consumption, maximum power, and low smoke levels; therefore, it is doubtful that large gains in ignition delay could be made through alteration of injection characteristics or air swirl motion.

The largest reductions in ignition delay will most probably result from changes in the chemical delay. For any given fuel, the chemical delay is a strong function of the cylinder temperature into which the fuel is injected. Thus, methods were sought to increase cylinder temperature at the time of injection without degrading overall engine performance.

The low cetane performance optimization task was initiated in Phase II. The objective of this study was to improve engine performance using fuels whose cetane numbers were significantly degraded from the No. 2 diesel fuel specification as well as to obtain at least acceptable engine performance on fuels of poorer quality than the engine can currently tolerate. Constraints were placed on the manner in which these improvements could be achieved. Modifications or adjustments to the engine must be relatively simple, straightforward and readily adaptable to existing field engines. For example, the parameters that were adjusted during Phase II to improve low cetane performance included injection timing, fuel temperature, intake air temperature and pressure, and injection spray pattern. Ignition delay of low cetane number test blends decreased slightly when using these techniques, but the reductions were not sufficient to reduce knock levels or improve thermal efficiency appreciably.

The final technique evaluated during Phase II proved successful. A small portion of the low cetane fuel was injected as a pilot through a second injection system before the remainder of the fuel charge, using a technique called "staged injection". The pilot acted as an ignition source and eliminated knocking of fuels with cetane numbers as low as 24. This technique was deemed worthy of further investigation and was therefore included as a Phase III program task. Also evaluated during Phase III was the emulsification of water into low cetane number fuels.

The low cetane test fuels were blends of high aromatic naphtha (HAN) and DF-2. In neat form, HAN possessed a cetane number of 17.7, but its density, heating value, viscosity and distillation range were nearly the same as that of baseline DF-2. When HAN was mixed with diesel fuel, the resulting blend had a cetane number that was proportional to the quantity of the two components, but other fuel properties were essentially the same as DF-2. Thus, the cetane number could be varied independently of the other fuel properties for test purposes. Blends possessing cetane numbers of 30.8 and 24.0, as well as neat HAN at 17.7, were tested. The properties of these blends are presented in Table 7.1.

Table 7.1 Low Cetane Number Fuel Analysis

	Baseline	HAN	Low Cetane Number Fuel Blends	
Cetane Number	48.8	17.7	30.8	24
API Gravity @ 60°F	36.6	26.8	31.2	29.2
Kinematic Viscosity at 40°C (cSt)	1.53	1.47	1.85	1.65
Higher Heating Value, (BTU/lb)	19850	18965	19345	19400
Distillation (°F)				
IBP	364	347	352	350
10%	428	383	396	392
50%	502	431	456	442
90%	578	492	544	520
EP	614	536	615	595

Performance of the two-cylinder EMD engine on the HAN/DF-2 blends was mapped during Phase I (see Figure 7.1). As indicated, start of combustion is delayed significantly by the low cetane number blends, resulting in increased rates of pressure rise and audible knocking. Thermal efficiencies below baseline levels were observed at Notches 4 through 8, but slight improvements were noted at Notch 2. These performance levels provide a basis for comparison when attempting to improve low cetane fuel performance. The upcoming performance curves and text refer to "normal" 30.8 or 24.0 cetane number performance values. The "normal" values for the two-cylinder engine operating in standard configuration on these fuels are those presented in Figure 7.1.

Low Cetane Number Fuel/Water Emulsions

Attempts were made to use water emulsions to control the initial rate of combustion and reduce knocking of low cetane number fuels. Water emulsions were considered because of research success in reducing fuel consumption and smoke levels on smaller laboratory engines. Although exact mechanisms by which these improvements occur are not known, several theories have been hypothesized; these are discussed in Section 8.3. It was felt that these mechanisms might prove useful for improving low cetane number fuel consumption and that the cooling effect might slow the initial rate of combustion.

The unstabilized water emulsions were prepared using the on-line emulsifier shown in Figure 7.2. This unit was built by Fuels Systems Design Corporation. The system first mixed the two fuel components in a tee, then in a gear pump, and finally in a venturi that was kept in cavitation. Emulsified fuel was pumped by the shortest, most turbulent path, from the emulsifier to the unit injectors to prevent separation. The large main fuel filters, where separation was seen to occur, were bypassed. The smaller secondary paper filters could not be easily bypassed, so they remained in the circuit. Return fuel containing both water and test fuel was not returned to the fuel storage tank because separation would occur. Instead, return fuel was pumped to the inlet of the emulsifier where it was remixed and consumed. A schematic of the emulsifying system is shown in Figure 7.3. Baseline DF-2/water emulsions were evaluated first, followed by 30.8 cetane blend/water emulsions. Tests were performed at Notches 4 and 8 only (see Figure 7.4).

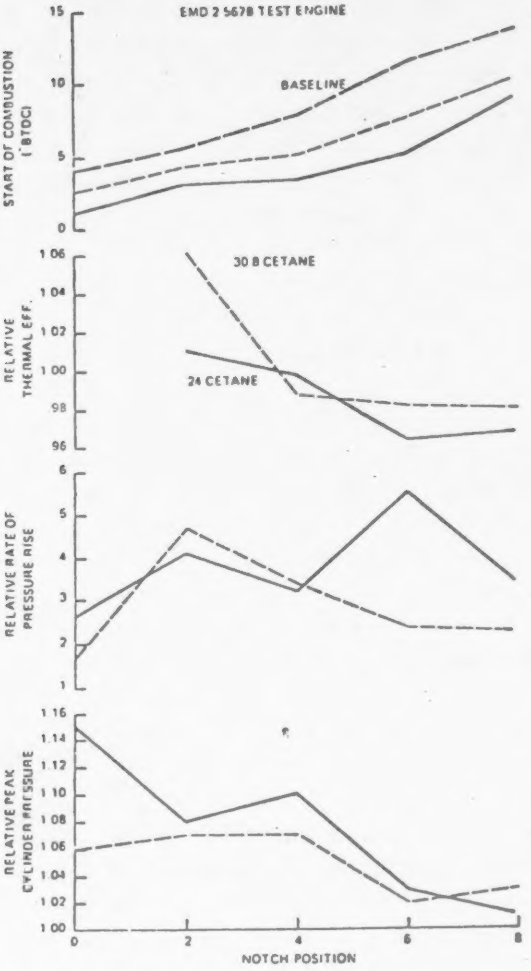


FIGURE 7.1 TWO-CYLINDER EMD ENGINE PERFORMANCE ON LOW CETANE NUMBER FUEL BLENDS IN CONVENTIONAL INJECTION CONFIGURATION

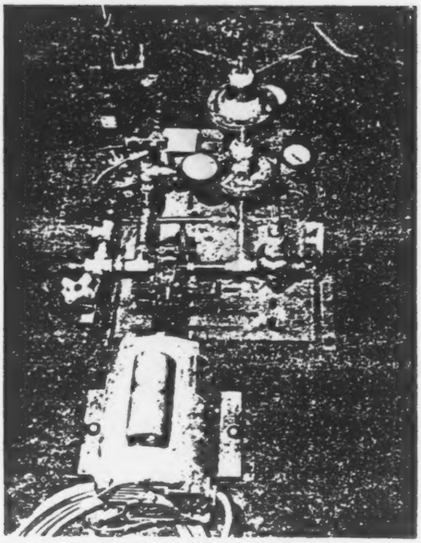


FIGURE 7.2 TWO-CYLINDER EMD ENGINE WATER/DIESEL FUEL EMULSIFIER

The water emulsions did not meet the test objective - to reduce knock. In all cases, knocking increased with water content of the emulsion; therefore, the test schedule was abbreviated and single data points were recorded at the majority of the test conditions.

The emulsions daily test procedure required the engines to be started, warmed up, and checked at Notch 8 on DF-2. Water was then added while the engine was running. In all cases, the first few test points recorded after water was added indicated a dramatic increase in thermal efficiency; however, points recorded later in the same day at the same water percentage failed to duplicate these optimistic results. The problem was attributed to errors in the fuel flow rate measurement induced by fuel pressure surges from the closed-loop emulsifying system. Normally, the Flo-tron is installed in an open loop arrangement that includes a surge tank vented to atmospheric pressure to nullify such surges. No attempt was made to correct the problem since the test schedule was abbreviated.

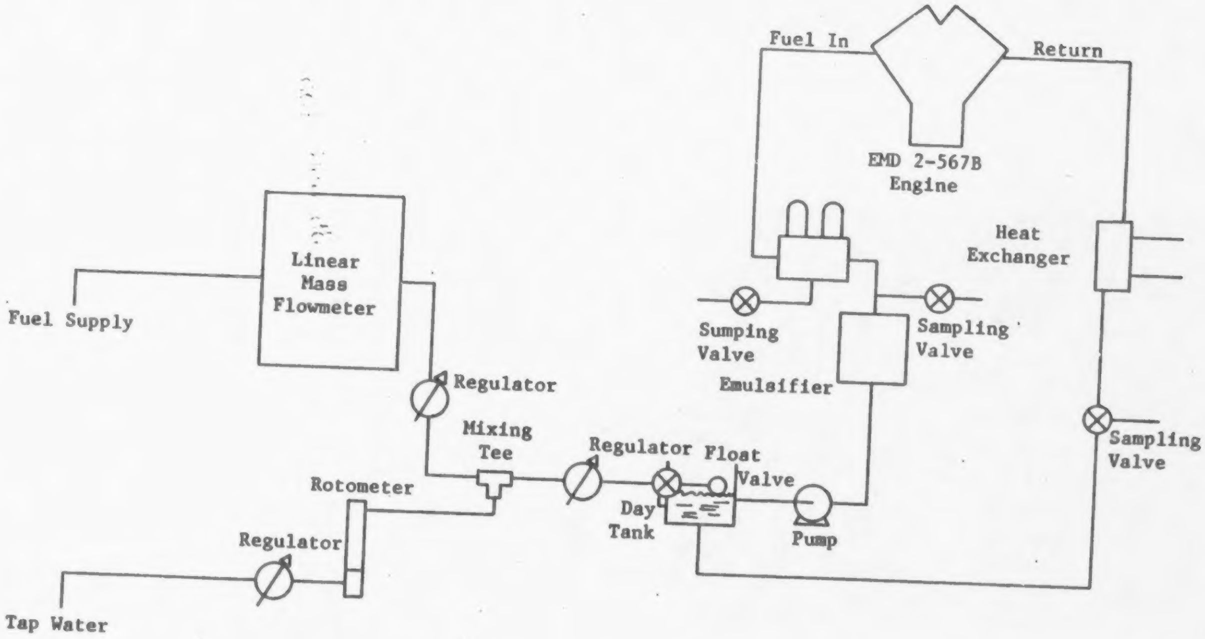


FIGURE 7.3 EMULSIFYING SYSTEM 2-567B

Emulsions containing up to 21 and 28 percent volume water in baseline DF-2 and 30.8 cetane number blend, respectively, were tested. Ignition delay, rate of pressure rise, and peak cylinder pressure increased as water content increased at both notches. Audible knocking was detected at 21 percent water on baseline DF-2. Knocking was detected at the lowest percentages tested on the 30.8 cetane blend, 4 percent at Notch 4 and 8 percent at Notch 8, and increased in intensity with water content. The results of the tests at Notches 4 and 8 are presented in Figures 7.4 and 7.5.

Brake thermal efficiency at Notch 8 fell within ± 1.5 percent of baseline on both DF-2 and 30.8 cetane blend, regardless of water concentration. The majority of thermal efficiency values obtained at Notch 4 were at or above the baseline value; because of the fuel flow rate measurement problem, thermal efficiency values were badly scattered (see Figure 7.5). Some large improvements in thermal efficiency occurred, but, while directionally correct, the magnitude of these increases should not be considered realistic. The small amount of repeat data taken with DF-2/water emulsions showed that differences as great as 13 percent occurred at the same water concentration.

Bosch smoke decreased from a baseline value of Bosch 1.0 to 0.4 on all water emulsions tested at Notch 8. The minimum water content evaluated was 7.5 percent volume. Smoke values at Notch 4 using neat diesel fuel at a Bosch 0.1 decreased below detection on water emulsions containing more than 5 percent water.

In summary, the water emulsions failed to achieve the desired objective, to reduce knocking of low cetane number fuels. Knocking increased with water emulsion content. However, the emulsions showed benefit in reducing smoke, and possibly in improving thermal efficiency. The water emulsions may be of benefit when using No. 2 diesel fuel or alternative fuels of good cetane quality. Water emulsions are discussed further in Section 8.3 in this context.

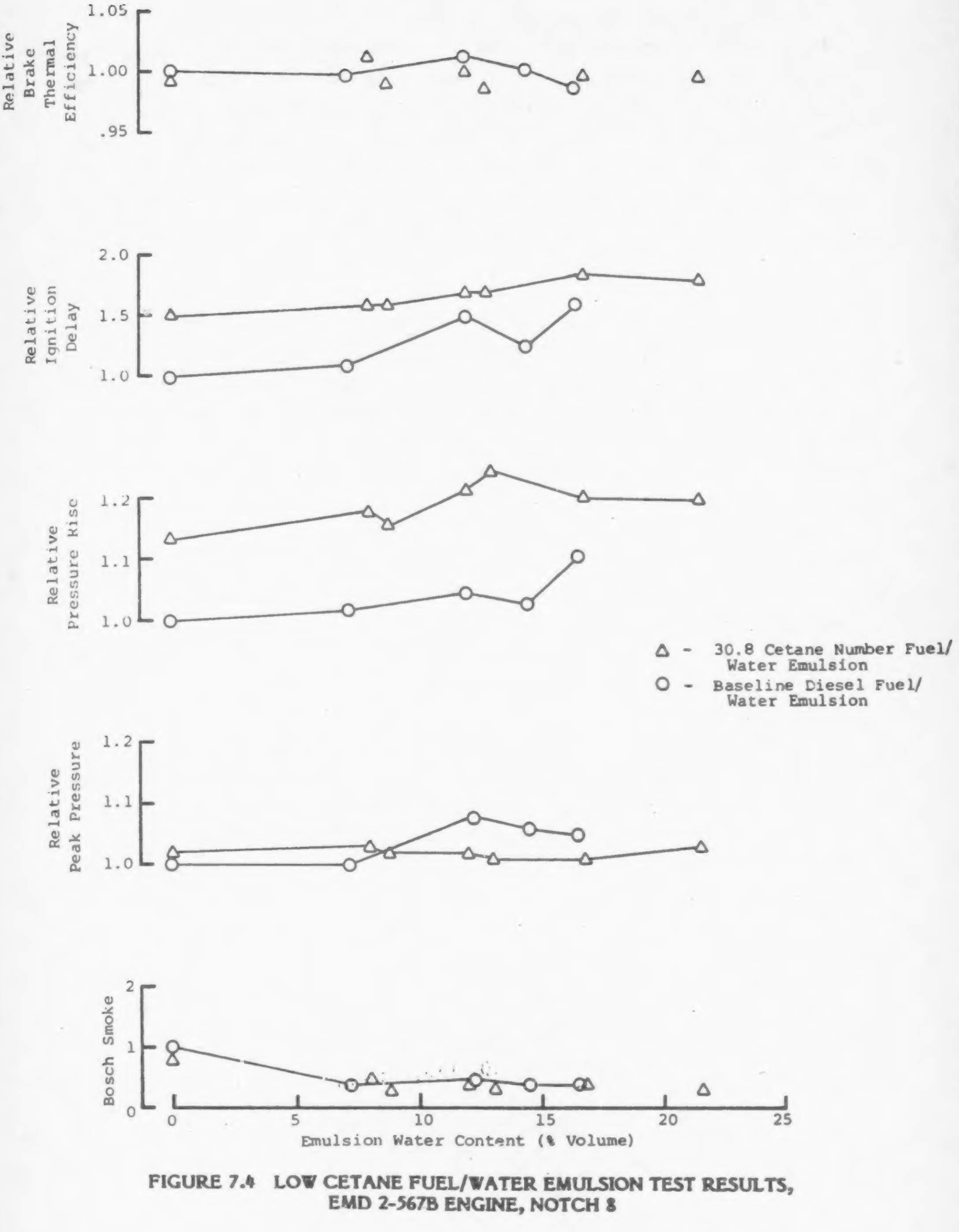


FIGURE 7.4 LOW CETANE FUEL/WATER EMULSION TEST RESULTS, EMD 2-567B ENGINE, NOTCH 8

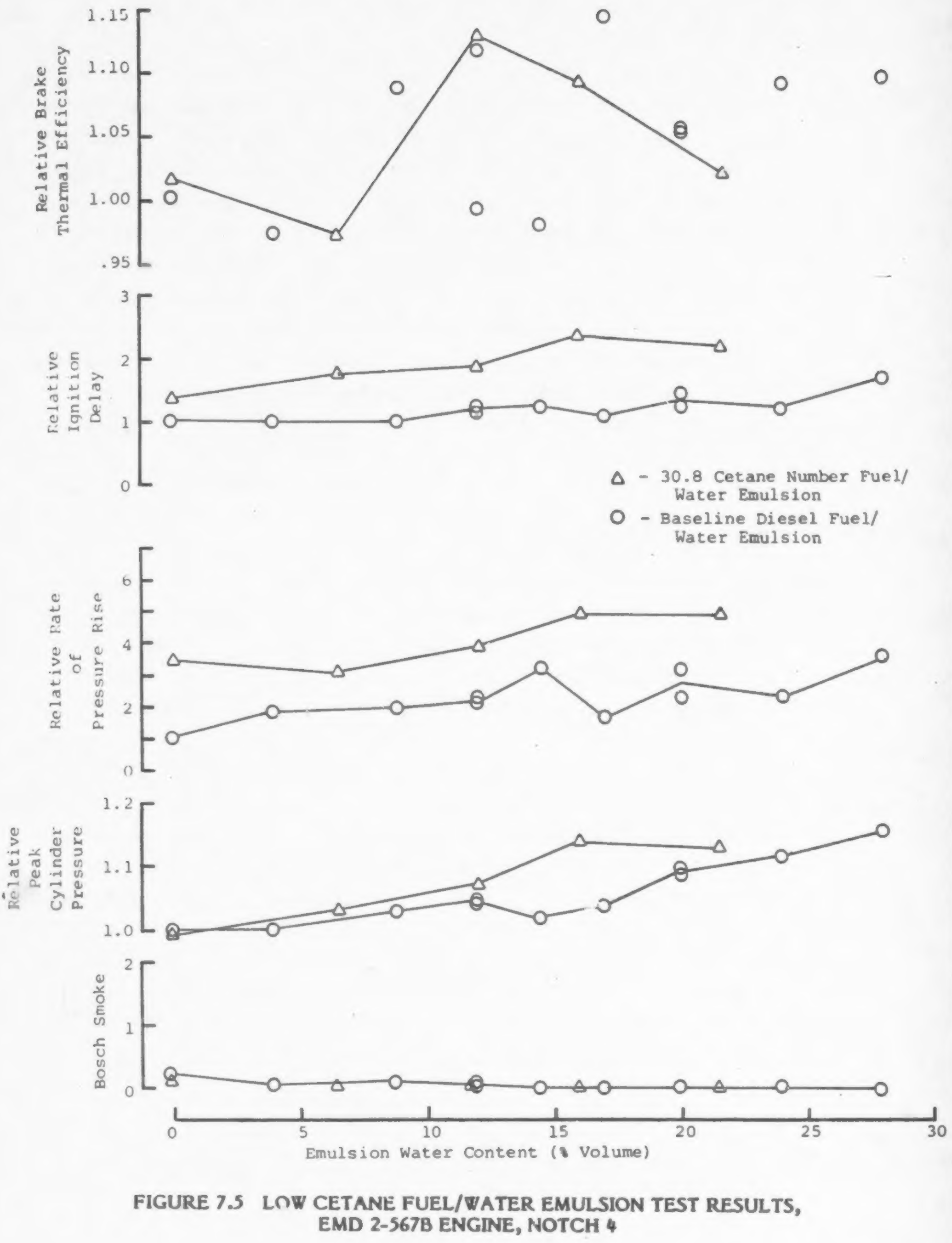


FIGURE 7.5 LOW CETANE FUEL/WATER EMULSION TEST RESULTS, EMD 2-567B ENGINE, NOTCH 4

Staged Injection

Experiments were conducted on the two-cylinder EMD engine to study further the potential for using staged injection to improve low cetane number fuel performance. Staged injection was first studied during Phase II and found to be quite successful in reducing knocking, while yielding good thermal efficiencies. As the name implies, staged injection is the injection of the fuel in several stages. Only two stages have been tested thus far, a pilot and a main injection stage. In the first, or pilot stage a small portion of the fuel is injected early in the compression stroke and burned before the main charge. This portion is too small to produce significant knock levels, but effectively increases the cylinder temperature before main injection. The main fuel charge is then injected into a high temperature, burning environment where it ignites rapidly, thus eliminating the long ignition delay period that is responsible for knocking. The pilot and main stages are the same fuel.

The idea for staged injection evolved from dual-fuel tests using pilot diesel fuel as the ignition source. While this method is very effective for consuming high percentages of low cetane alternative fuels, it has the drawback of requiring two fuels. The logistics of storing, handling, and carrying two fuels are complicated, and the conversion to add a second injection system for pilot diesel fuel is extensive. Matters would be greatly simplified if the pilot diesel fuel charge could be replaced with the same alternative fuel used for main injection and a single injector could handle both pilot and main stages. Single injection systems with multiple injection characteristics that eliminate the need for dual injection pumps and nozzles have been built and tested(12).

The concept of multiple fuel introduction is not new. Various permutations of the idea have been studied by several researchers(13,14). Obert refers to early introduction of a fraction of the fuel as "fuel preconditioning" and defines three known techniques: pilot injection, Vigom injection, and fumigation(13). Pilot injection is the injection of a small fuel charge during the compression stroke, usually 30 to 60° BTDC. This is followed, a few crank angle degrees later, by main injection. Vigom injection differs in that the initial injection is some 320 to 350° BTDC into the hot residual gases remaining in the combustion chamber after the exhaust stroke. As a result, Vigom injection applies only to four-stroke engines. Fumigation refers to mixing of fuel with intake air prior to induction into the combustion chamber. Staged injection employs the same fuel preconditioning concept as pilot and Vigom injection, but pilot injection timings and injection techniques differ. These variations are discussed in detail below.

Staged injection was achieved during Phase II on the two-cylinder EMD engine using two separate injection systems. EMD unit injectors supplied the main fuel charge while a secondary injection system handled the pilot fuel. The secondary injection system was added by enlarging the pressure relief (blowdown) port in each cylinder head to accept a small diameter pencil nozzle. This arrangement is shown in Figure 7.6. The pencil nozzles penetrated the combustion chambers approximately one inch from the liner wall. A two-hole spray pattern with an included angle between the plumes of 70° was used and both plumes were injected at an angle of 18° below the cylinder. Fuel was supplied to the nozzles by a pair of single plunger injection pumps installed at the rear of the engine. These pumps were driven directly off of the generator shaft through a differential timing mechanism, permitting wide variations in pilot injection timing (Figure 7.7). The unit injectors were fitted with six-hole tips and their timing was fixed at the manufacturer's specification throughout these tests. Fuel rates for main and pilot fuel were controlled independently of each other. All staged injection tests were performed on an equivalent BTU basis (see Section 5.2).

The Phase II experiments demonstrated that staged injection was a successful means of controlling ignition of low cetane number fuels. The 30.8 and 24.0 cetane number HAN/DF-2 blends were tested over a wide range of pilot injection timings and pilot injection quantities. Knocking was eliminated with the proper combination of pilot timing and injection rate. The best pilot timings were quite advanced, ranging from 60° at Notch 4 to 115° at Notch 8. The percentage of fuel injected as the pilot varied, depending on the fuel cetane number and the notch position, but 20 percent was typically required for smooth, knock-free combustion on the 30.8 and 24.0 cetane number blends. Unfortunately, thermal efficiency at the 20 percent pilot inputs was less than that at lower pilot percentages, but the efficiencies were well improved over fueling on the low cetane blends without pilot injection. The best combination of pilot timing and fuel rate resulted in thermal efficiencies ranging from 2 to 4 percent below baseline DF-2 values.

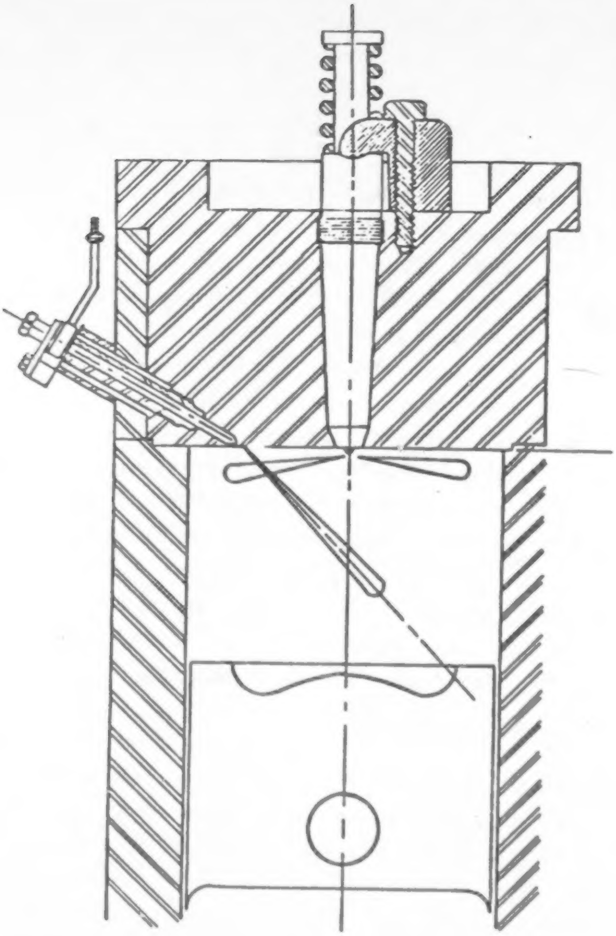


FIGURE 7.6 LOCATION OF PILOT AND MAIN INJECTION NOZZLES

Poor thermal efficiencies were assumed to result from improper injection of the pilot charge. The two-hole pencil nozzles were designed for good fuel distribution and penetration at injection timings ranging from 30 to 40° BTDC. The injection timings that proved most successful for staged injection ranged from 60 to 115° BTDC. As a result, the pilot fuel spray may have impinged on the liner wall due to the low cylinder pressure and low piston position at the advanced timings.

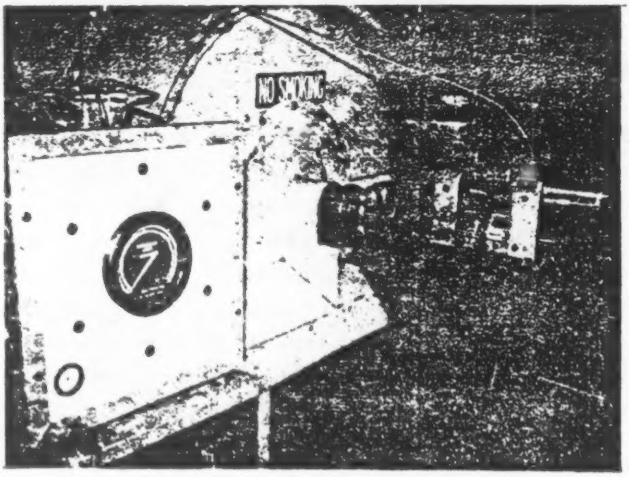


FIGURE 7.7 PILOT INJECTION SYSTEM SINGLE PLUNGER JERK PUMPS DRIVEN THROUGH A DIFFERENTIAL TIMING DEVICE

The Phase III staged injection experiments attempted to improve low cetane performance by modifying the pilot injector spray pattern. A one-hole pattern with a spray angle of 48° below the cylinder head was selected. This spray pattern was designed to prevent liner wetting at injection timings up to 115° BTDC. Aside from this change, the equipment employed was identical to that used during Phase II. Baseline DF-2 and 30.8, 24.0, and 17.7 cetane number fuel blends were tested at Notches 4 and 8 with pilot timings ranging from 30 to 115° BTDC. The amount of fuel injected as the pilot charge varied from 5 to 15 percent.

The modification to the pencil nozzle spray pattern resulted in marked improvements in low cetane fuel performance. Again, injection of a small portion of a low cetane fuel at the pilot stage very effectively reduced knocking; however, far less pilot fuel was necessary to achieve the same results produced by the two-hole spray pattern. For example, a 5 percent pilot charge produced cylinder pressure characteristics and thermal efficiencies comparable to baseline DF-2 on the 30.8 cetane blend at Notch 4; previously, a 20 percent pilot charge was needed. The improved control of the pilot charge over start of combustion permitted operation on the 17.7 cetane number blend. The lowest level previously tested was 24 cetane number fuel.

Baseline DF-2 was first tested with the one-hole pencil nozzles. Staged injection performance results at Notches 4 and 8 were poor. The crank angle position at which combustion started was a function of the amount of pilot fuel injected and the pilot injection timing. In all cases, the alterations made were detrimental to performance, either causing reduced thermal efficiency or increased combustion noise. Thermal efficiency decreased as the quantity of pilot fuel injected increased. Efficiencies above baseline values occurred at Notch 4 using 5 percent pilot, but erratic combustion (from cycle to cycle) made operation at these points undesirable. Notch 8 thermal efficiencies registered below baseline with the exception of a single 5 percent pilot case. It was concluded that staged injection is not warranted on fuels of high cetane rating and can actually be detrimental. Performance figures for the DF-2 staged injection experiments are presented in Appendix A.

Staged injection performance results on the 30.8 cetane number blend were more promising than those on DF-2. Knocking was eliminated by using 5 percent pilot at Notch 4 and 10 percent at Notch 8. Pilot injection timings of 60° and 115° BTDC at Notches 4 and 8, respectively, provided the best combination of thermal efficiency and smooth combustion. Thermal efficiency at Notch 4 was approximately 2 percent above DF-2 baseline, but was 2 percent below baseline at Notch 8.

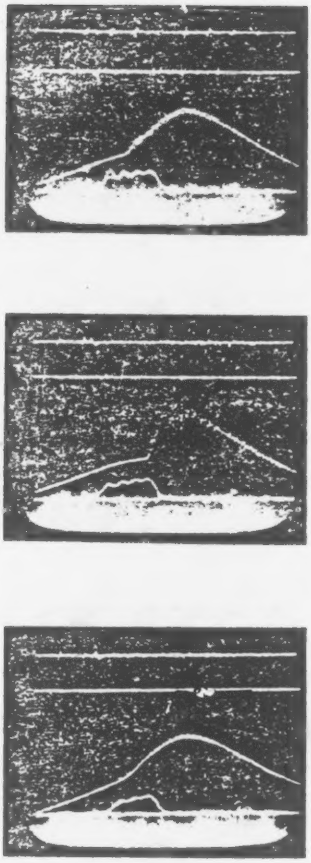
The pilot percentages and injection timings that worked best on 30.8 cetane fuel were optimum for the 24.0 cetane fuel as well. Smooth combustion without signs of knocking was achieved at both Notches 4 and 8 and thermal efficiencies were at the same levels as those of 30.8 cetane fuel. The performance plots for the 30.8 and 24.0 cetane experiments are presented in Appendix B

A slightly higher percentage of pilot fuel was necessary to control combustion of the 17.7 cetane blend. Performance at Notch 4 using 15 percent pilot was excellent. Knocking was virtually eliminated, as can be seen on the cylinder pressure traces presented in Figure 7.8, and thermal efficiency was equal to the baseline value (Figure 7.9). At the lower pilot percentages, knocking was a problem and varied in intensity with the timing; unfortunately, the lowest pilot percentage produced the highest thermal efficiencies.

Performance at Notch 8 was not as smooth as performance at Notch 4, but was close to baseline levels and greatly improved over normal 17.7 cetane operation. Rate of pressure rise was only 20 percent above baseline when using 15 percent pilot, but cyclic combustion irregularities generated higher audible combustion noise levels than baseline diesel fuel. Thermal efficiency was within 1 percent of DF-2 baseline at the best combination of 15 percent pilot at 100° BTDC injection timing (Figure 7.10). It is possible that the combustion irregularities could be eliminated by increasing the pilot percentage to 20 percent.

Smoke levels were, in general, lowest at both the smallest pilot percentages and the most advanced pilot injection timings. As a result, smoke levels were not at minimum at many of the optimum operating points, but were at levels approximately equal to baseline DF-2, never exceeding a value of 1.0 on the Bosch smoke scale ranging from 0 to 10.

Qualitatively, the results of the staged injection experiments on the low cetane number fuel blends were quite successful. The two-cylinder EMD engine operated on fuels with cetane numbers as low as 17.7 without knocking and with reasonably good thermal efficiency. Further study of the pilot and main fuel injection rates, spray patterns, and timings might yield further improvements, such as use of less pilot fuel or increases in thermal efficiency, particularly where below baseline values. The mechanisms by which the pilot charge ignites the main fuel charge are quite complex and are not fully understood. Further research is needed in this area for the full potential of staged injection to be realized.



Standard No. 2 Diesel Fuel Operation

Standard Operation on a 17.7 Cetane Number Fuel

Staged Injection Operation on a 17.7 Cetane Number Fuel. Initial Stage Containing 15% of Fuel Input Injected at 80% BTDC

FIGURE 7.8 OSCILLOSCOPE CYLINDER PRESSURE TRACES TAKEN DURING STAGED INJECTION OPERATION AT NOTCH 4

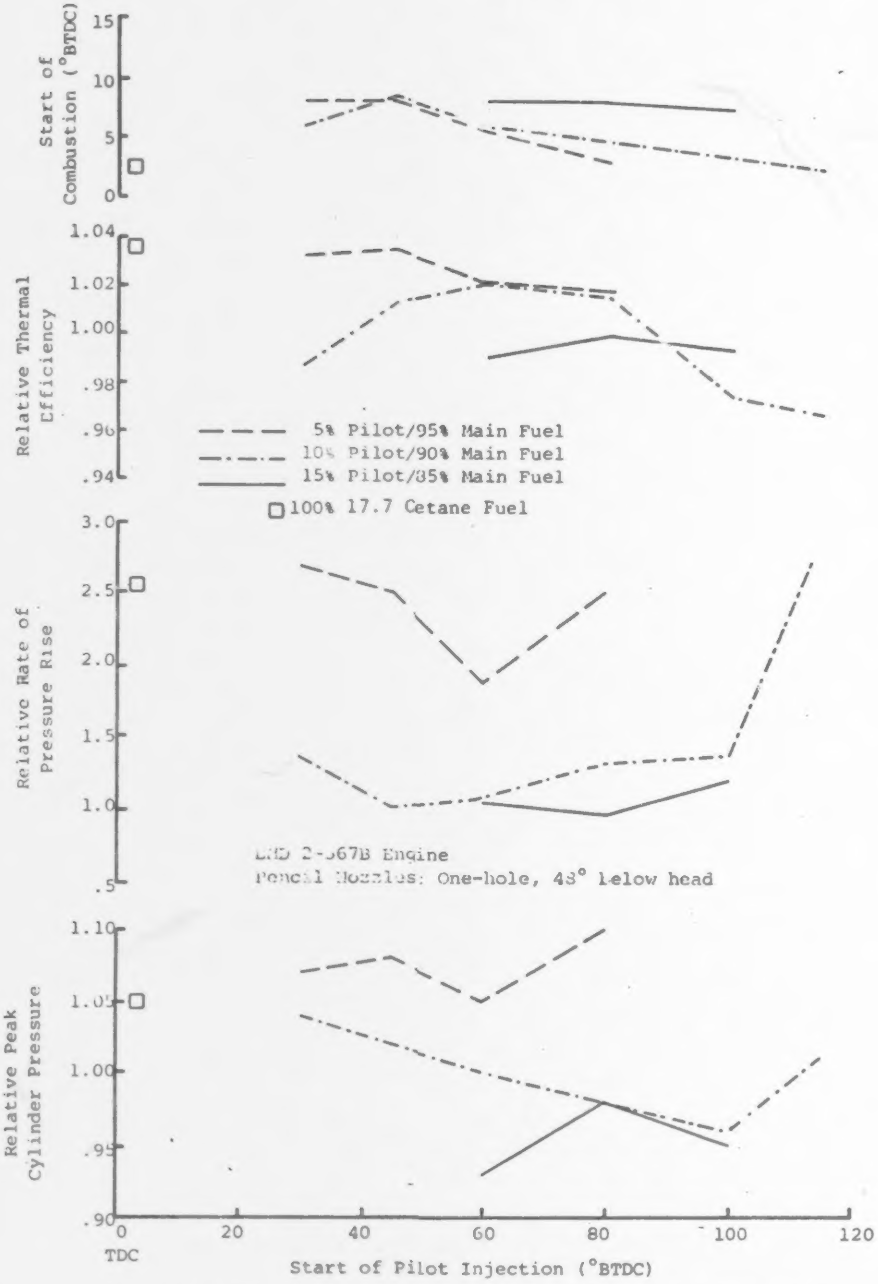


FIGURE 7.9 NOTCH 4, 17.7 CETANE FUEL STAGED INJECTION PERFORMANCE RESULTS

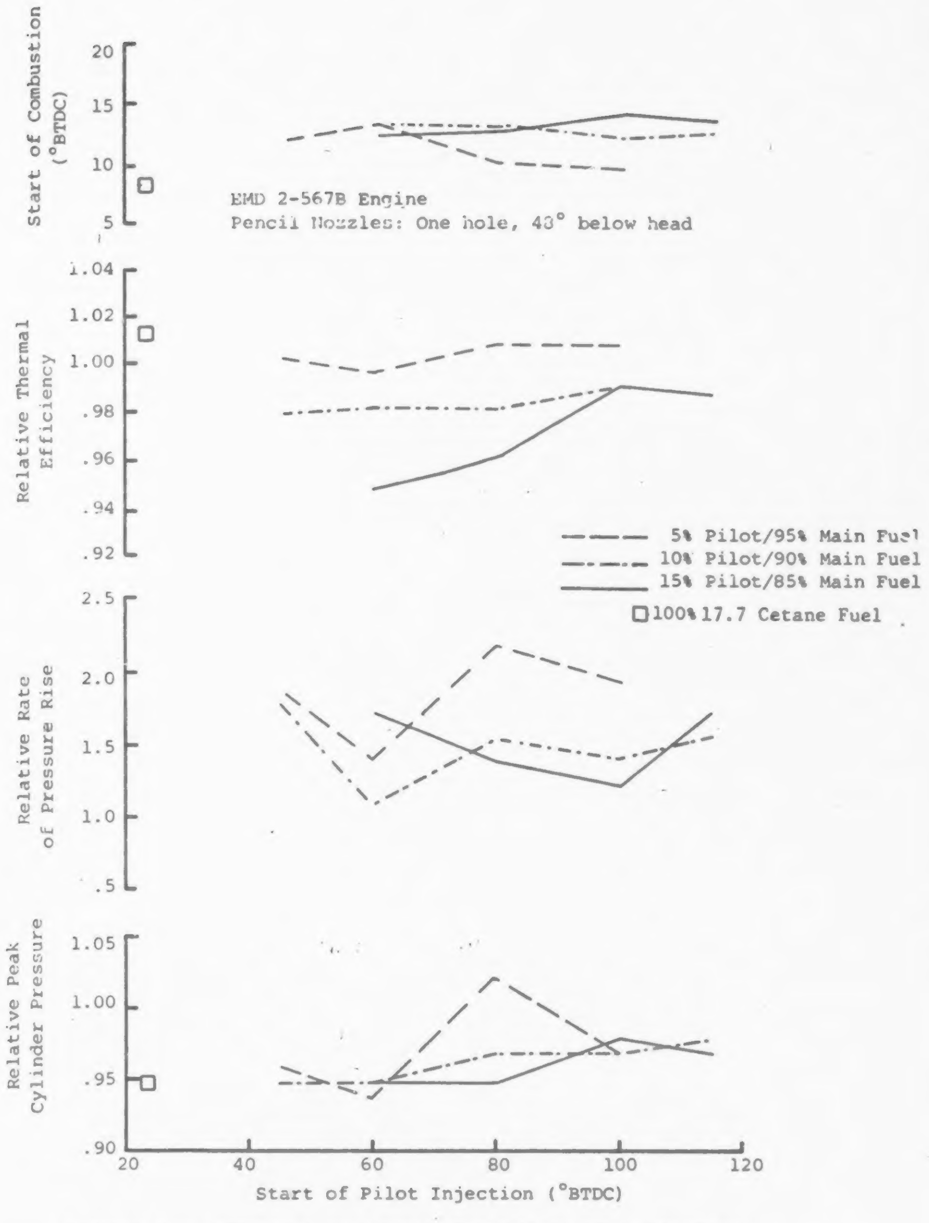


FIGURE 7.10 NOTCH 8, 17.7 CETANE FUEL STAGED INJECTION PERFORMANCE RESULTS

Reference 15 contains a more detailed discussion of staged injection for interested readers.

Methanol Staged Injection

Experiments using staged injection to control ignition of low cetane fuels proved successful on blends with cetane numbers as low as 17.7 at a compression ratio of 16:1. Burning still lower cetane fuels at this compression ratio may be possible, gauging by the success at 17.7 cetane. Methanol and ethanol, with cetane numbers of approximately 0, are potential alternative fuel sources for diesel engines; ignition is the primary obstacle that must be overcome before extensive use could be made of these fuels. Staged injection may be one means of igniting the alcohols at a reasonable compression ratio. (Compression ratios on the order of 23 or 25:1 are required to compression ignite these alcohols in a direct injection diesel engine.) It is doubtful that staged injection of either alcohol would be effective at the 16:1 compression ratio; however, experience with methanol in the two-cylinder engine during a previous program showed that methanol would compression ignite at 20:1, but that severe knocking would also occur.(16) There is a good possibility that if a small pilot charge could be compression ignited, it would provide a suitable ignition source for the main alcohol charge.

The EMD two-cylinder engine was converted to 20:1 to evalute methanol staged injection. This was accomplished by installing 20:1 pistons, the 645 high output unit injectors, and the secondary injection system. The high output unit injectors were capable of injecting sufficient methanol for full baseline heat input up to Notch 5; above this position, additional methanol input had to be provided by the pencil nozzles. Tests were performed at Notch 6, which required a minimum of 5 percent methanol input as pilot fuel.

The one-hole pencil nozzles that were used during the above low cetane staged injection experiments were again employed. The needle valve of one of these nozzles seized after the first two attempts to test alcohol pilot injection, and it was necessary to switch to available two-hole pencil nozzles (with sprays angled 18° below the cylinder head and 70° between the plumes). The one-hole pencil nozzles had been installed in anticipation of using extremely advanced pilot injection timings. In the final analysis, the extremely advanced timings were not successful and the switch to the two-hole nozzles was appropriate.

Attempts to use methanol staged injection on the two-cylinder EMD engine were unsuccessful. The small charge of methanol injected as the pilot would not effectively start combustion of the main charge. Very severe knocking accompanied by random misfiring characterized the operation at Notch 6, the only notch tested. Unfortunately, no performance data were recorded because of the very unstable behavior of the engine; engine speed and power fluctuated over large spans. The most important piece of information, the cylinder pressure trace, was not obtained due to repeated pressure transducer failure in the severe knocking. On several occasions, it became necessary to shut the engine down to avoid damage. Thermal efficiency of the engine was also very poor. Engine power was approximately one-half that of the baseline value when injecting full baseline heat input. Heavy white smoke was evident.

As mentioned above, the extremely early pilot timings did not prove successful. A very narrow range of pilot timings (between 20 and 50° BTDC) were the only positions at which sustained combustion would take place. Beyond this range, misfiring occurred the majority of the time and the engine rapidly lost speed. It was evident that pilot injection was necessary for repeated combustion to occur. If pilot timing was retarded to start at the same time as main injection, the engine would not fire. Therefore, the pilot charge must have compression ignited before the main charge and acted as an ignition source, but the pilot was too weak an ignition source for repeated ignition of the main charge.

The effects of the volume of pilot methanol injection and spray orientation are not known. A stable operating condition could not be maintained long enough to explore these parameters. If combustion of the pilot charge could be improved, staged injection might be feasible. A further increase in the compression ratio is the first step, but other methods such as intake air heating or altered pilot spray orientations may prove beneficial.

Neat methanol was consumed during all staged injection attempts. When methanol was injected through the unit injectors during previous dual-fuel experiments, a small proportion of DF-2 was emulsified into the alcohol to serve as a lubricant for the close fitting injector components. The injectors worked without fault when using the lubricant, but no data was available for neat methanol. Two incidents occurred during the staged injection tests with alcohol that indicated lubrication was needed. A pencil nozzle valve seized in its guide after a short period of operation, and a pair of the unit injector needle valves began leaking. These failures occurred in a very short time; the total operation on neat methanol did not exceed ten hours. The unit injector needles were badly varnished.

Inspection of the engine components following methanol staged injection revealed scuffing on the cylinder liners above the air ports of both cylinders. The scuffing is not surprising considering the volume of unburned methanol present in the cylinder. Research on laboratory spark ignition engines has shown that scuffing is likely any time raw methanol is deposited on the cylinder walls.(17)

While the methanol staged injection tests were unsuccsessful, the approach may be feasible and should be considered if methanol is seriously considered as a main locomotive engine fuel. If staged injection can be made to work properly, it will allow operation on 100 percent methanol at a lower compression ratio than is needed with direct injection compression ignition of methanol. This compression ratio would not be as low as that used when dual-fueling using pilot DF-2. Potential cold starting problems with methanol staged injection are an additional reason that dual-fueling should also be considered.

7.2 CARBON BLACK/DF-2 SLURRIES

The effects of carbon black/DF-2 slurries on the fuel injection system and performance of the two-cylinder EMD engine were studied. Slurries are a potential alternative fuel form that this program has not previously addressed. Solid materials that would not normally be feasible as a fuel for diesel engines may possibly be used as diesel fuel extenders through slurries .

The objectives of the slurry fuel task were:

1. To determine the type and composition (particle size and concentration) of slurry that would be best suited for use in a medium-speed diesel engine.

2. To determine the effects of this slurry on the fuel handling and injection systems.

3. To evaluate the performance and wear characteristics of the slurry in the two-cylinder EMD engine.

A review of research data on slurry fuels was undertaken as the initial step in this study. Based on this material, the type of slurry to be tested was selected. Potential problem areas were identified and used as guidance in developing a test plan. The effects of the slurry on injection system and fuel transfer systems were studied through bench tests using actual two-cylinder engine components. Following successful completion of the bench tests, slurries of varying concentration were tested in the two-cylinder engine for performance and wear effects.

Test Fuel Selection and Formulation

A research project was initiated in 1979 at SwRI to develop and investigate the potential of hybrid fuels. The project, sponsored by the U.S. Department of Energy, resulted in the development and testing of a wide range of fuels, including a variety (entirely separate from this program) of slurry fuels. The results of the Hybrid Fuels program provided the basis for selection of the AFFMSDE program slurry material and of the method of engine operation. A detailed description of the Hybrid Fuels program can be found in references 18 and 19.

The Hybrid Fuels program developed and tested ten different slurry fuels; their properties are presented in Table 7.2. The solid materials used were classified into two groups: hard fragmentable and soft, fibrous materials. Generally, the carbons fell into the hard fragmentable group while the raw biomass materials fell into the second category. This division became important since the particle size of the hard, fragmentable materials could be easily reduced to that needed for rapid combustion, but the soft, fibrous materials could not, making them poor candidates for slurries.

Table 7.2 Properties of the Slurry Fuel Formulations

Fuel	Net Heat of Combustion (kJ/kg)	H_2 wt%	C_2 wt%
Neat DF-2	45659	12.84	86.62
10% Coke	41556	11.56	87.96
20% Coke	40728	10.27	89.29
10% Carbon Black	41349	11.56	87.96
20% Carbon Black	40060	10.27	89.29
20% Coal	39607	11.82	83.89
20% Cellulose	27467	13.3	86.75
20% Starch*	---	---	---
20% Mesquite Wood*	---	---	---
20% Flour, 1% Lecithin	36751	---	---
20% Coke, 80% Methanol*	---	---	---

* These fuels would not run in the engine.

Several slurries tested on the Hybrid Fuels program caused sticking of the nozzle valve within the injector. The particle size of the solids in the slurries was limited to less than 10 microns to alleviate this problem. Particles below this size would pass through the injection system and, in addition, completely burn within the available time for combustion in the engine. As added insurance against sticking, the clearance between the nozzle valve and nozzle body was increased by 0.25 mm to ensure that the particles would flow through the clearance area.

Carbon black was selected as the best choice for a slurry material for the AFFMSDE program for several reasons. Carbon black was commercially available in small particle sizes and formed the most stable slurries during the Hybrid Fuels program. A stable slurry could be formed by careful selection of the base particle sizes, absorption characteristics, and concentration of the carbon black. Carbon black was also found to be the least abrasive of the hard, fragmentable materials. Abrasiveness was an important criteria since wear in the barrel and plunger of the injection pump is one of the main drawbacks to slurry use.

The carbon black selected from those commercially available was the Mogul-L produced by Cabot Corporation. A standardized procedure was devised to blend this product with DF-2. First, the carbon black was added to DF-2 and stirred. The mixture was allowed to stand for at least 24 hours to ensure complete absorption of the diesel fuel into the solid material. Immediately before engine testing, the mixture was processed in a laboratory homogenizer for at least one-half hour to break up agglomerates. Homogenization continued until photomicrograms of the slurry indicated that all particles were less than 10 microns in diameter (Figure 7.11). The fuel was continuously agitated while stored using a pneumatic stirrer. If allowed to stand, the carbon black would re-agglomerate into larger particle sizes.

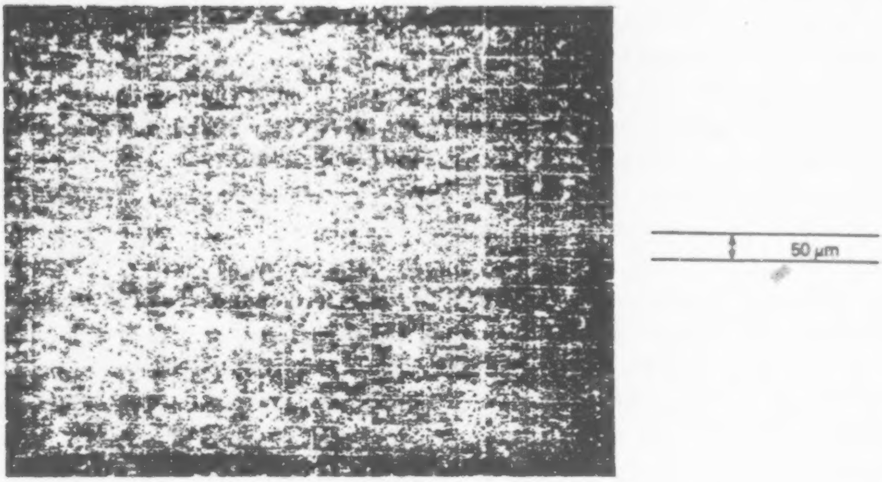
The Hybrid Fuels program indicated that the use of slurries introduces four basic injection systems problems (jerk pump systems were tested exclusively). These problems are:

1. Plugging of the orifices in the injection nozzles.
2. Sticking of the nozzle valve.
3. Wear in the barrel and plunger of the injection pump.
4. Degraded or reduced degree of fuel atomization.

The first three problems are related to the durability of a given injection system, while the fourth problem deals with the system performance characteristics. The durability aspects were addressed briefly through injection system bench tests while the performance evaluation was conducted during engine testing as described below.

Injection System Bench Tests

The bench tests were broken into separate tests of the filtration, fuel transfer pump, and unit injector systems. The filtration system consisted of a fuel pump forcing slurry through two large (primary) EMD cotton sock filters, followed by two small (secondary) EMD pleated paper-type filters. A pressure gauge was installed before and



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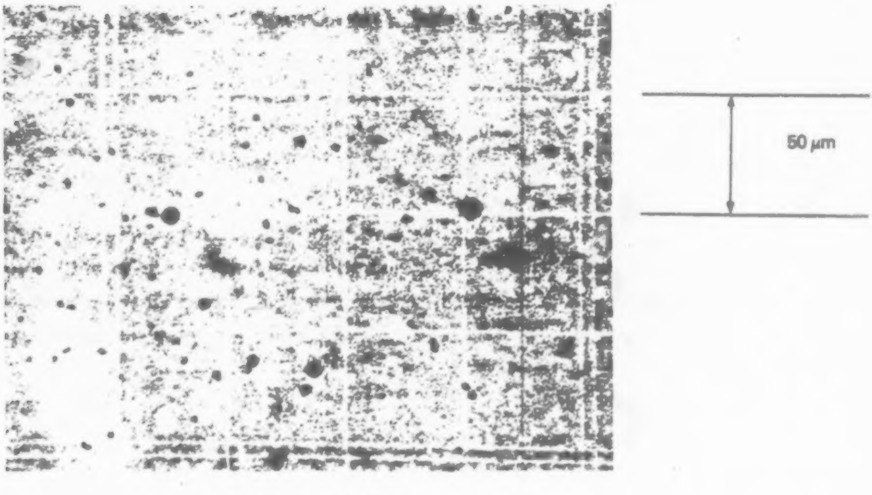

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FIGURE 7.11 PHOTOMICROGRAMS OF CARBON SLURRY

after each filter housing. Filter plugging could be determined by an increase in the pressure drop across the filters.

The fuel transfer pump system consisted of a Tuthill cast-iron rotary gear pump with a pressure bypass set at 60 psig that drew slurry from a 55 gallon drum and returned fuel to another drum. A gear pump was selected for evaluation since this appeared to be the type most commonly on the locomotive engines.

The unit injector test stand was constructed using EMD 567 series components. Basically, the test rig consisted of a camshaft segment mounted on an EMD cylinder head with the standard rocker arm arrangement attached. The camshaft segment was driven by an electric motor through a variable ratio gear reduction system. Fuel was supplied to the injector by a laboratory plunger-type slurry pump. Test stand instrumentation included strain gauges fitted to the injector rocker arm, a speed (rpm) readout, and a fuel mass flow rate measurement system on the fuel discharge side of the injector (Figure 7.12). The strain gage signal was monitored as an indicator of either increased or decreased pumping forces. Abnormalities in the strain signal were caused by a change in friction between the barrel and plunger in the injector, or sticking of the nozzle valve. The fuel rate was monitored to indicate reductions in injector pumping capacity or reductions to slurry flow restriction due to nozzle wear. Wear was expected between the barrel and plunger, which would increase leakage, reducing injector pumping capacity.

Slurry concentrations of 5, 10, and 20 percent by mass were tested. Fuel was pumped from a 55 gallon drum through each of the three test systems until either signs of plugging or malfunction of components occurred. The fuel passed through a system only once to ensure that the slurry concentration and particle size were not changed due to shearing.

The fuel filtration bench test was of very short duration - both filters plugged within the first hour of testing. Carbon black would not pass through either the pleated paper or cotton sock filters. A thick carbon sludge was left on the outside of each filament. It was concluded that fuel filtration of the carbon black slurries is not possible or practical.

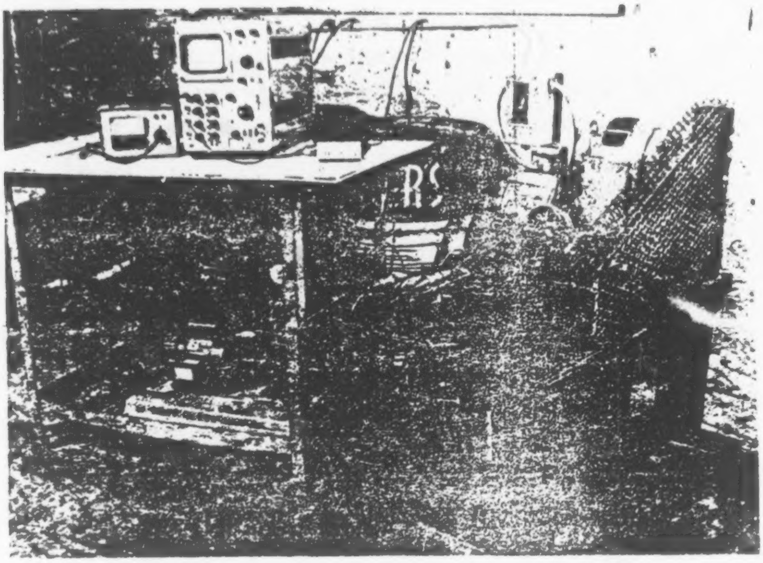


FIGURE 7.12 UNIT INJECTOR TEST STAND

The effect of the carbon slurry on the cast-iron rotary gear pump was studied next. The rotary pump had accumulated 50 hours of combined testing (part of this in conjunction with the injector tests below) on 10 and 20 percent carbon black slurry with no appreciable drop in flow rate or pressure. However, disassembly and inspection of the pump revealed abnormal wear. Indications of wear were present on the pump idler, idler pin, crescent and rotor. Even though performance of the pump was still good at the completion of testing, the pump would undoubtedly have failed with further operation. A slurry pump suitable for extended use must be found to replace the present transfer pumps.

The third step in the bench test consisted of the unit injector evaluation. Testing was performed at Notch 8 conditions; 835 rpm and a fuel flow rate of 6.5 gallons per hour. The injector was operated for approximately 6.5 hours with each slurry, then dismantled and inspected. The 10 percent concentration slurry testing went smoothly; inspection of the unit injector did not reveal any sign of unusual wear.

However, the injector needle was seized in the valve body after 6.5 hours of running on the 20 percent slurry. The needle could not be removed from the valve body; it was necessary to split the body to free it. Inspection of the wear surfaces revealed a black glaze buildup between the needle and body, causing interference between the two parts. This failure verified the results of the Hybrid Fuels programs.

Photomicrograms taken of both the 10 and 20 percent slurries indicated that the carbon agglomerate size decreased after injection. This reduction was responsible for a large increase in slurry viscosity noted during each test. It is believed that the unit injector performed in much the same manner as a crushing mill to break up the carbon particles, thus increasing particle surface area and subsequently slurry viscosity.

Carbon Slurry Engine Performance Tests

A complete set of piston and cylinder measurements were taken and new unit injectors were installed before engine tests began. The primary and secondary fuel filters were removed from the two-cylinder engine fuel system. A flush mounted pressure transducer was installed in one cylinder to permit high-speed data acquisition.

Concentrations of 5, 10, 15, and 20 percent by mass carbon black in DF-2 slurries were evaluated in the engine. Standard performance parameters as well as high-speed computer cylinder pressure data were recorded at Notches 2, 4, 6, and 8. The engine was operated on baseline DF-2 before and after each slurry test and performance was checked in each case. Typically, two to three replicate tests were run with each fuel to establish satisfactory data confidence. Power output was held constant at baseline values during all slurry tests.

Performance data for the two-cylinder engine experiments on carbon black slurries are presented in Figures 7.13 and 7.14. A 4.1 and 8.8 percent reduction in thermal efficiency was encountered with the 15 and 20 percent carbon concentrations, respectively. Smoke increased drastically with the 20 percent slurry but did not change significantly at lower concentrations. The slurry mass flow rate increased with the concentration of carbon black to maintain constant power. The increased flow rate was

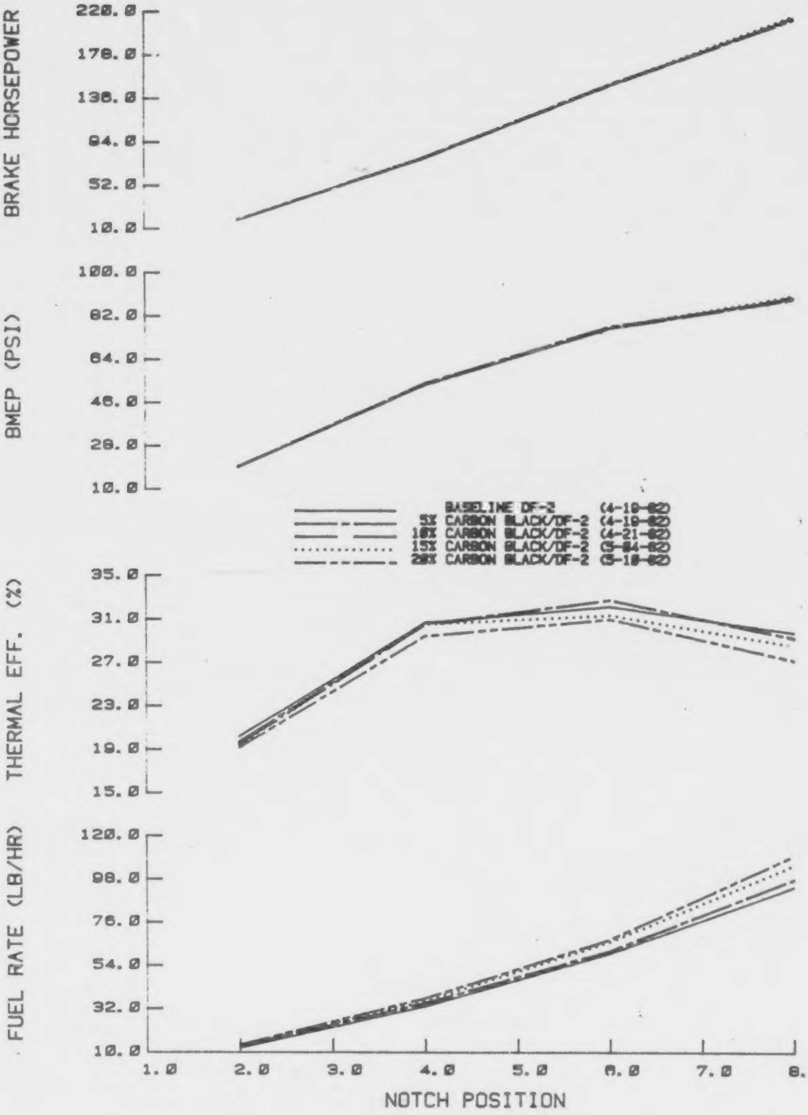


FIGURE 7.13 EFFECTS OF CARBON BLACK/DIESEL FUEL SLURRIES ON EMD 2-567B ENGINE PERFORMANCE

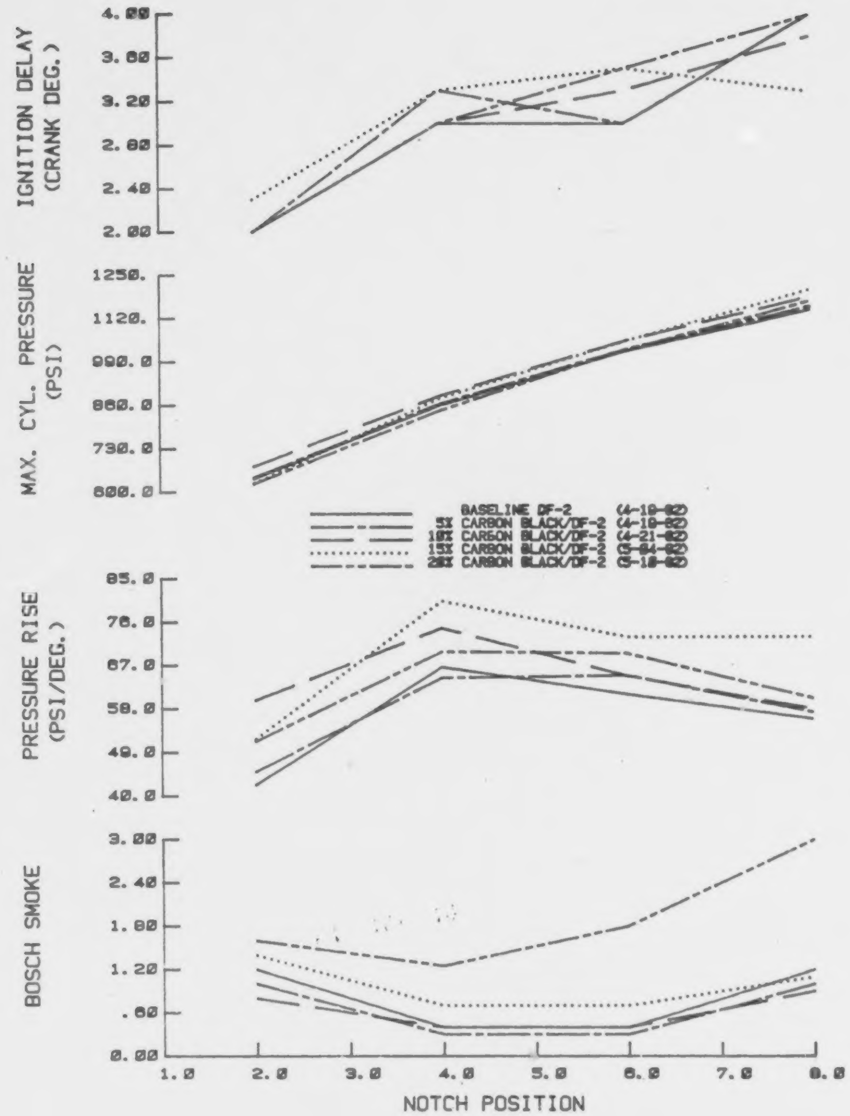


FIGURE 7.14 EFFECTS OF CARBON BLACK/DIESEL FUEL SLURRIES ON EMD 2-567B ENGINE CYLINDER PRESSURE AND SMOKE CHARACTERISTICS

expected since the energy content (BTU/lb) of the carbon slurries decreased as carbon black content increased.

The carbon slurry tests were not without problems. A unit injector needle seized open during a test of the 15 percent slurry, causing heavy carbon sludge buildup around the piston rings and in the liner ports (Figure 7.15). Inspection of the injectors revealed a glaze buildup on the needle and valve body identical to that seen during the injector bench tests. The clearance between the needle and valve body was increased by .001 inches for subsequent tests at 15 and 20 percent concentrations; no further problems were encountered during these brief tests.

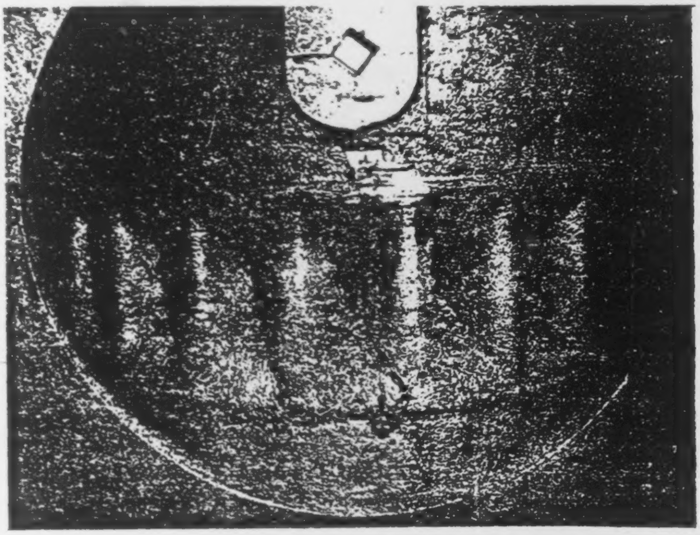


FIGURE 7.15 HEAVY SLUDGE BUILD-UP AROUND EMD LINER PORTS

The engine was disassembled and inspected following slurry testing. Severe ring and liner wear were found. The engine had acquired a total of only 40 hours of operation. During this period the top two compression rings were worn to the extent that the witness grooves were completely removed. The witness grooves are wear indicators on the face of the ring that are inset to .040 inches. Ring wear measurements are presented in Table 7.3. Both cylinder liners exhibited severe scuffing. Scuffing was also noticeable on all moving injector components. Wear to this degree normally requires extensive engine operation under severe conditions.

Table 7.3 Piston Ring Wear

LEFT SIDE WEAR

	End Gap Increase (inches)	Width (inches)	Weight Loss (ounces)
Top	0.042	0.001	.1799
2nd	0.020	0.0006	.0423
3rd	0.042	0.0003	.1129
4th	0.013	0.0068	.0106
5th	0.0	0.0	.0106

RIGHT SIDE WEAR

	End Gap Increase (inches	Width (inches)	Weight Loss (ounces)
Top	0.041	0.0003	.1870
2nd	0.020	0.0010	.0776
3rd	0.043	0.0	.1129
4th	0.041	0.0	.0106
5th	0.007	0.005	.0141

The slurry tests demonstrated that it is possible to burn a carbon black/DF-2 slurry in a medium-speed diesel engine with good thermal efficiency, but that extensive developmental work will be needed in the areas of fuel handling, injection, and engine durability. Commonly used fuel pumps will wear quickly and carbon compaction in pipe joints is likely. Injection pumps must be redesigned to prevent excessive wear in the closely fitted barrel and plungers, and needle valves. Engine experiments should be conducted to determine the cause of the high ring and liner wear encountered on the two-cylinder engine.

The slurries are potential alternative fuels for the medium-speed diesels, but should be ranked as low priority. They are not acceptable emergency fuels and are not a near term substitute for diesel fuel because of the development needs.

7.3 CYLINDER WEAR MEASUREMENT TECHNIQUES

The cylinder wear measurement task investigated various methods for determining cylinder liner and piston ring wear in laboratory medium-speed diesel engines. Cylinder wear is an important consideration with any alternative fuel, but wear tests are lengthy and costly in these high durability engines. Direct measurement of engine parts is probably the most reliable method of obtaining average long-term wear data, but the engine must be operated for a minimum of 500 hours to achieve measurable wear and it must be disassembled for measurement before and after each test. The purpose of this study was to find a cylinder wear measurement technique that would provide accurate liner and ring wear data in a relatively short period (less than 100 hours) on a laboratory test engine.

The objectives of the wear measurement task were to:

- Analyze available wear measurement methods and determine the suitability of these methods to this program
- Select the best method from those uncovered, and implement this method on the EMD 2-567B engine
- Determine the EMD 2-567B cylinder wear rates when operating on baseline DF-2 fuel and an alternative fuel
- Assess the feasibility of applying the wear measurement method to the 12-cylinder laboratory engines.

The first step in the study was to conduct a literature search on wear measurement methods. The most promising of these methods was selected and adapted to the two-cylinder EMD engine. A standard engine test procedure was then developed to ensure repeatable wear results. Attempts were made to determine the wear rate of No. 2 diesel fuel and a high sulfur diesel fuel.

iterature Search on Wear Measurement Methods

A literature search identified a number of wear measurement methods that ere roughly grouped into four categories: direct mechanical measurement, dynamic ıeasurement techniques (measurements taken during engine operation), exhaust gas ltration, and lubrication oil analysis. Each of the techniques is described below, and n assessment of the suitability of these methods to medium-speed diesel engines is rovided.

Direct Mechanical Measurement is the most reliable technique for obtaining verage long-term wear data. The engine is disassembled prior to testing, the omponents of interest are weighed and measured, and the engine is reassembled and perated for a predetermined length of time. The engine is disassembled at the onclusion of the test and the components are again weighed and measured. While eliable, this method is time-consuming and laborious.

Dynamic Measurement Techniques have the potential to generate wear meaurements while the engine is operating. Methods identified included the Sulzer ntegrated Piston Ring Wear Detecting Arrangement (SIPWA), capacitive and resistive iner wear sensors, inductive piston ring condition sensors, and ultrasonics. The Sulzer echnique uses a patented piston ring with a wedge-shaped groove machined into the ace of a cast iron ring. The groove starts at the top at one end of the ring, and spirals lown the face to terminate at the bottom edge at the opposite end. This band produces ι wear dependent signal when passing a sensor mounted in the cylinder wall. The otational position of the piston ring can be determined by measuring the interval ›etween the edge of the piston ring and the edge of the wear band. Radial wear can be letermined to an accuracy of ± .02 mm with large diameter rings (900 mm). Jnfortunately, the Sulzer methods cannot be utilized with smaller bores for short term ⁄vear analysis. The width of the wear band is critical to obtain measurable wear figures. The face of a medium- or high-speed diesel ring is simply not wide enough to nstall this groove.

Resistive and capacitive sensors are other examples of dynamic wear methods. These sensors are installed in cylinder liners and determine the wear of the liner surface at the location of the probes. The resistive sensor consists of a resistive circuit embedded in a dialectric material. The face of the sensor wears with the liner surface and changes the resistance of the circuit, which can be correlated directly to liner wear. A limitation of this method is that only one point on the liner can be measured per sensor. The location selected for measurements should be in an area where greatest wear is expected. The capacitance probe measures the gap between the face of the sensor and the opposite metal surface; it must be mounted slightly below the surface of the liner. A liner thickness measurement can be made when a piston ring is positioned opposite the face of the sensor. This method may not provide accurate data while the engine is running due to the variability of the oil film thickness between the piston ring and the liner, but it may be feasible for static measurements.

Utrasonics is the only technique identified that offered the potential for both piston ring and cylinder liner wear measurement. An ultrasonic transducer is mounted in the cylinder liner and transmits ultrasonic waves at a constant frequency. As the piston rings pass the sensor, the ultrasonic waves are projected through the piston ring and the reflection of the waves from each metal surface is recorded by the transducer. It is not necessary to drill a hole completely through the liner to mount the transducer; rather, the ultrasonic waves can be transmitted through the wall of the liner. The distance from the face of the transducer to the inner liner surface, and from both the front and rear ring, faces can be determined. Ultrasonics have not been attempted on an engine, but the problems of timing, temperature, and environmental appear to be surmountable. Instrument specifications show accuracies on the order of ± .0005 inch, which is not sufficient for a 100 hour duration wear test in which liner wear is expected to be on the order of micro-inches. As a result, ultrasonics appear to be feasible only for long-term wear measurements.

Exhaust Gas Filtration - This is another unproven wear measurement technique that, at this point, has not been attempted. It is theorized that a quartz filter can be installed in the exhaust system of an engine to trap wear metal particles removed from the cylinder liner and/or piston rings that are swept into the exhaust stream. An absolute wear measurement is, of course, not possible since not all of the material removed from the piston rings and cylinder liners will be entrained in the exhaust stream. A relative comparison of wear between two alternative fuels may be possible. This method is highly speculative.

Lubrication Oil Analysis - Two known methods fall within this category: radioactive tracer and spectrographic oil analysis. The top compression ring is irradiated for radioactive tracer testing. As this ring wears, radioactivated metal is washed into the oil sump. The radioactivity level of the oil is monitored as an indicator of wear rate. The radio-tracer technique has been used successfully on medium-speed diesel engines and was attempted (unsuccessfully) during Phase I on the two-cylinder engine. This technique is undesirable on medium-speed diesel engines due to the large mass (the top compression ring) that must be irradiated and the volume of contaminated oil that must be handled.

Spectrographic techniques monitor the concentration of metals in the lube oil through spectrographic analysis of oil samples as an indicator of ring, liner and bearing wear rate. This technique is used in many medium-speed diesel field applications to monitor engine condition and determine intervals for oil change. The oil samples can be drawn from any location in the engine and can be analyzed for most elements higher in molecular weight than sodium. A drawback for use in short-term wear analyses is that the concentration of metals must be sufficiently high for detection, which the National Research Council of Canada (NRCC) overcame by drawing oil samples directly off of the liner wall where metals concentrations were highest. The NRCC work is discussed in more detail below.

The selection of the wear measurement method for use in this program was dictated primarily by the ability of the method to detect very small dimensional changes in the rings and liner. For example, 300 hour duration oil certification tests performed on the two-cylinder EMD engines at SwRI indicated that cylinder liners are likely to wear at a rate of .0002 inch (diameter) per 100 hours operation on DF-2. Such levels of wear were at or below the lower level of detection of the resistive, capacitance, and ultrasonic methods during the desired period of testing. Exhaust gas filtration, as mentioned, is unproven and highly speculative. The radioactive tracer method is undesirable because of the handling problems associated with the radioactive ring and contaminated oil. Thus, by process of elimination, spectrographic oil analysis was the only method with the capability of determining the desired wear rates within a 100 hour period.

Spectrographic oil analysis was studied by NRCC using an EMD 567C series engine in the late 60's(21). Small holes were drilled through the cylinder liners to draw samples directly off of the liner walls where wear metals concentrations were high. NRCC conducted tests on an 18.5 hour cycle studying the effects of cylinder liner materials, fuels, and lubricating oils, and found that the method was capable of detecting large changes in wear rates. This work established the basic feasibility of the technique to determine short-term wear characteristics of cylinder liners and piston rings. NRCC investigated experimental aspects (i.e., engine modifications and sampling hardware) and procedural considerations (engine test sequence and spectrographic analysis method), and determined either optimum or workable methodologies.

Two-Cylinder EMD Wear Tests

Information obtained from NRCC reports and technical papers was used as the starting point for this program. NRCC drew individual cylinder oil samples directly off of the liner wall by installing a sample orifice in the cylinder liner of the 567C EMD locomotive engine, 1.75 inches above the air intake ports. The orifice, 0.78 inch in diameter, was sufficient to supply approximately 10 cc of oil in one to two hours of engine operation at all conditions. Locating the hole slightly above the air intake ports resulted in a pressure-fed oil sample as the piston traveled downward on its expansion stroke. The EMD two-cylinder engine was modified in the same manner for this program.

An area of concern during spectrographic testing is the increase in crankcase sump oil metals concentration with time. Simply monitoring the concentration of metals in oil samples from the liners is not adequate for an accurate wear rate determination. Wear metals are likely to settle to the bottom of the sump or be trapped on the oil filters, making it difficult to relate changes in concentration to wear rate. Some form of a reference or background concentration is needed. NRCC chose to change the oil in their test engine frequently to keep the background concentration very low. Unfortunately, even during a short test, the sump oil is contaminated with wear metals and the sump oil metals concentrations increase. To overcome this problem, a background oil sample was taken during two-cylinder engine tests. This was drawn from the "pee" tube that directs oil into a hole in the underside of each piston, which cools the piston and lubricates the piston pin and thrust washer. This oil is pressure-fed from the crankcase sump and is the source of the bulk of the oil that reaches the liner walls. A background sample from the "pee" tube was taken at the same time as a cylinder liner oil sample. The background sample concentration was then subtracted from the liner oil concentration, providing a measure of the increase in metals concentrations due to ring and liner wear.

Sampling holes were located in double wall areas of the liner through which cooling water passed. It was necessary to drill the sampling hole in a steel fitting that sealed the inner and outer liner walls against both water and gas leaks (Figure 7.16). The fitting was pressed against the inner liner wall and was threaded into the outer wall. A 1/4 inch O.D. copper tube was attached to the probe and passed through a hole drilled in the air box inspection cover.

The oil samples collected from the cylinder liner probes were a mixture of oil and cylinder blowby or exhaust gases. A funnel was positioned under the end of each 1/4 inch sample line to allow the gases to escape while the oil dripped into the funnel.

The "pee" tube sample was drawn through a small fitting welded to the "pee" tube itself and passed out of the engine through a 1/4 inch copper tubing. This sample consisted entirely of pressure-fed oil, the flow being regulated by a needle valve at the end of the copper tubing at a very low rate so oil flow to the piston was not greatly affected. A 10 cc "pee" tube sample could be collected in several minutes, much less than the time required for liner oil samples. The "pee" tube samples were drawn at the end of a liner oil sampling period as a general practice.

Both cylinders were fitted identically with liner and "pee" tube sampling holes. This placed the liner sampling holes on the anti-thrust side on the right bank and on the thrust side on the left bank.

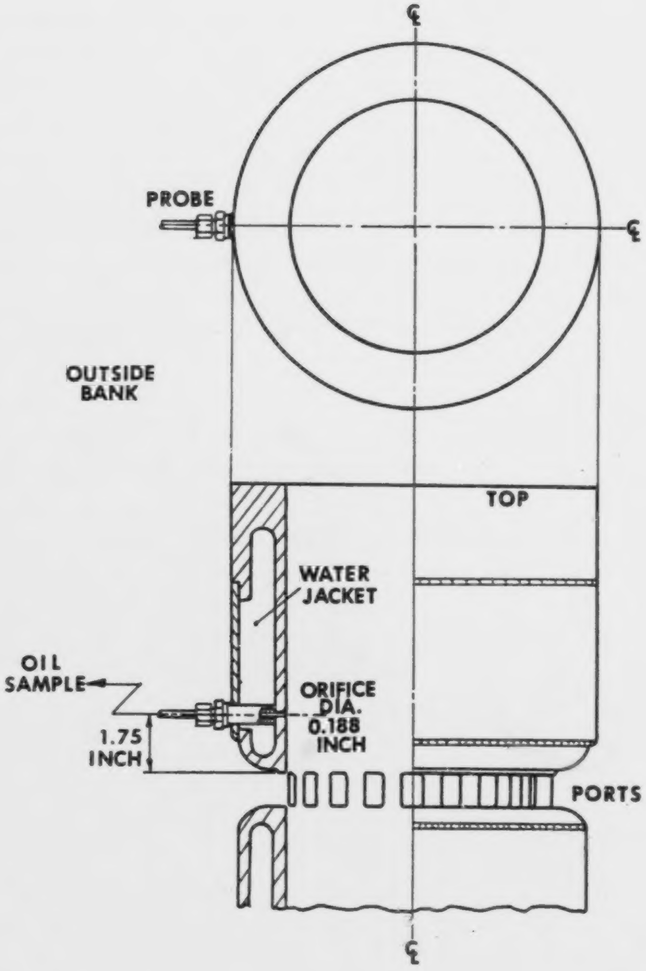


FIGURE 7.16 CYLINDER LINER OIL SAMPLING PROBE INSTALLATION

Four methods are commonly used to determine the metal content in lubricating oil. These are emission spectroscopy, atomic absorption, x-ray spectroscopy, and the use of a radioactive tracer. A description of each can be found in Appendix C. After weighing the advantages and disadvantages of the four methods, the x-ray spectroscopy method was selected for use during this study.

The first attempt to conduct wear tests using the arrangement described above was unsuccessful. Liner sampling holes did not supply enough oil for spectrographic analysis. A good deal of gas escaped through the sampling lines, but little entrained oil was extracted. Orifice size was enlarged to a diameter of 0.188 inch to increase the oil flow rate.

Several notch positions were tested to determine the best engine operating condition for wear testing. Notch 8 was evaluated first since this was believed to be the notch position that would generate the highest wear. Unfortunately, the flow rate of oil from the liner sampling hole was extremely low, with essentially no sample collected after two hours. It was suspected that the Notch 8 piston speed was high enough to limit the amount of oil carried up the cylinder walls by the piston rings, limiting the amount of oil sample collected. A greater volume of oil was collected over the same time increment at Notch 4, but the flow rate was still quite low. Two hours were required to collect sufficient oil for analysis (approximately 4 grams).

Baseline wear tests were conducted at Notch 4 to establish a reference wear level. The engine was operated continuously for 100 hours with oil samples taken every two hours. A total of four oil samples were collected during each test point, one from the liner and "pee" tube of each cylinder. All remaining wear tests were conducted at Notch 4 and were of 100 hours duration.

The oil samples taken from the engine during the wear tests were analyzed by energy dispersive x-ray fluorescence for concentrations of chromium and iron. The chrome concentrations were indicative of wear from the rings, and the iron from the liners. The results of the Notch 4 baseline test were not very encouraging. The scatter in the data was quite high. This band of chromium concentrations was nearly 40 ppm between the maximum and minimum readings, with an average of 25 ppm and a standard deviation of 13 ppm for both cylinders. The concentrations of iron particles were less than that of the chrome and data scatter was again high.

The scatter was believed to be the result of the sampling method. It was not attributed to the x-ray fluoresence oil analysis, which was accurate to within ± 2 percent. Inconsistencies of the oil samples taken from the liner walls, both in volume and concentration, were the main factors. The oil flow rate was very low, requiring nearly two hours to accumulate a large enough oil sample for spectrographic analysis. Rotation of the pistons and rings coupled with the irregular flow of oil that is scraped down or splashed down onto the liner walls led to these inconsistencies.

A naturally occurring one percent sulfur fuel was tested to see if a change in wear rate could be detected when using a severe fuel. Initially, the chrome wear was quite high, but quickly fell to within the scatter of the baseline tests. Iron concentrations also fell within baseline scatter. It was not possible to identify any changes in the wear rate attributed to the one percent sulfur fuel.

Analysis of the 100 hour baseline wear tests indicated that part of the data scatter could be due to a cyclic variation that occurred every 24 hours. Changes in the condition of the inlet air were suspected to be the cause. A heating system was installed on the air inlet, and intake temperature was held constant at 110°F at the air filter for a second 100 hour baseline test. Results from this test were inconclusive; again, the cyclic variation and high data scatter were present.

The next step in the wear analysis was to increase the severity of the test in an attempt to increase the sensitivity of the wear rate measurement. Piston ring and liner wear is predominantly a function of piston speed, piston side loading, and viscosity of oil on the liner. The most severe case is that in which piston speed and oil viscosity are low, and piston loading is high; the oil film thickness between the liner and the ring is at a minimum and increased metal-to-metal contact occurs. Thus, slow speed, high load, and high temperatures were selected for wear testing. The engine was operated at the Notch 4 speed (515 rpm) and maximum obtainable load with water temperature increased from 180 to 190°F. The maximum load was 95 psi BMEP as compared to 54 psi for normal Notch 4 operation.

Baseline DF-2 and the naturally occurring one percent sulfur fuel were wear tested for 100 hours at 515 rpm/95 psi BMEP. No significant improvements occurred in the amount of data scatter and no differences were evident between the wear rates of the baseline and high sulfur fuels.

The engineers that participated in the NRCC program were consulted regarding irregular flow of oil from the sampling locations, data scatter, and location of the sampling ports.(22) They suggested that the degree of data scatter may have been the result of poor repeatability of the spectrographic analysis and recommended that the samples be analyzed three times. Further, since the concentrations were taken as the difference between that of the "pee" tube and liner oil samples, the error may have been compounded when the two values were subtracted. NRCC did not use a background sample but frequently changed the crankcase oil to keep the metals concentration below 15 ppm.

The oil samples from the second 100 hours baseline test were subjected to two additional x-ray fluorescence tests as suggested, totaling three analyses each. The repeatability of the x-ray fluorescence was about 5 ppm with an average of 10 ppm. This degree of scatter was far too great for detection of small changes in wear metals concentrations while the average concentration was that low.

Other analytical methods for detection of wear metal were sought for improved sensitivity and repeatability. Analysis by atomic absorption and emission spectroscopy were recommended. Unfortunately, these tests could not be performed due to insufficient volume of the oil samples. Five milliliters of sample were required for each. The samples drawn from the hole in the liner wall were well below that volume.

Engine testing was terminated at this point. The power assemblies were removed from the engine, inspected, and components weighed and measured. These dimensions were compared with dimensions taken at the start of the spectrographic wear experiments to determine the magnitude of wear that occurred during approximately 700 hours of combined No. 2 diesel fuel and one percent sulfur fuel testing. Ring and liner wear was on the order of .004 inch measured 6 inches from the top, confirming that the one percent sulfur fuel indeed induced high wear rates. The witness grooves of the top compression rings were no longer visible, and only 50 percent of those on the second compression rings were visible. Normal engine operation wear is approximately half this magnitude.

The results of the two-cylinder engine spectrographic wear tests were not encouraging. The measurement could not detect a difference between the wear rates of a specification DF-2 and a one percent sulfur fuel. Inconsistencies in the flow rate through the hole in the cylinder liner wall as well as the metals content of the oil generated a high degree of data scatter that obscured detection of any changes.

It may be possible through continued research to obtain a short-term wear rate measurement (less than 100 hours) using spectrographic analysis. Suggested methods to increase the oil flow rate include adding several more liner sampling holes positioned in the same plane and combining the flow from them, and machining grooves in the inner surface of the liner to channel oil to sampling holes. The concentration of wear metals in the oil can only be increased by increasing the wear rate of the rings and liners. Higher temperatures and piston loads, and lower oil viscosities will increase wear rates. However, these changes in engine operating condition move the wear tests away from their original intent - to measure wear in common, representative medium-speed diesel engines. A direct correlation of the severe tests to field engines would not be available. Such a correlation could be developed by comparing field data to laboratory data for similar fuels, but this would take a considerable amount of time. New wear methods that have higher sensitivity should be sought in light of these problems.

7.4 SUNFLOWER OIL/DIESEL FUEL BLENDS

Interest in vegetable oils as alternative diesel engine fuels dates back as early as 1930. However, research and engine testing in this area was limited to nations having little or no domestic petroleum reserves. The possibility that petroleum-based fuels may not be available in sufficient quantities or at reasonable rates in the future has renewed interest in vegetable oils.

Recent use of vegetable oil as a diesel fuel alternative has primarily been centered around farm applications and agricultural equipment. However, research should not be limited to these areas alone. The medium-speed diesel engines, with their proven fuel tolerance capabilities, are candidates for these fuels. Further, the similarity in vegetable oil and DF-2 properties makes vegetable oils some of the most probable emergency or substitute fuels.

There are a great many types of vegetable oils (corn, cottonseed, olive, peanut, safflower, sesame, soybean, and sunflower). Sunflower oil (SFO) was evaluted in this program. It was representative of vegetable oils in general and at least potentially available in sufficient quantities in the future to constitute a viable alternative fuel. SFO is typical of most vegetable oils in the pertinent properties of viscosity, API gravity, pour point, cetane number, and heat of combustion, which was the main consideration for selection.

A literature search on the use of vegetable oils was undertaken as the first step in this task. Although ample literature was available on this subject, much of it was redundant and the majority of the tests were poorly run or poorly documented. The tests were frequently performed on farm equipment and were intended not as research programs but as demonstrations of the feasibility of using vegetable oils. The properties of vegetable oils were well defined, and in some instances, good engine performance data was available, but a thorough study of the effects of refining on vegetable oil properties and, subsequently, on engine performance had not been undertaken. Durability had not been addressed, although problems with combustion chamber deposits and filter clogging when using partially refined oils were documented. As a result, a fully refined sunflower oil was chosen as the test fuel for this study.

The fuel purchased was a food quality SFO, although an oil of this quality was not needed. The supplier was unable to draw oil from the production stream before it was bleached and deodorized for food use. A less expensive oil could be obtained if these steps were omitted.

A small quantity of neat sunflower oil, DF-2 and the blends of these two components in 25 percent increments, were subjected to standard diesel fuel property determinations. The results of these tests are presented in Table 7.4. The cetane number of neat sunflower oil at 37.0 was slightly lower than DF-2 and viscosity at 31.9 cSt was an order of magnitude higher. The higher heating value of the sunflower oil was approximately 13 percent below that of diesel fuel. Sunflower oil was high in oxygen content, and consequently, was somewhat unstable as indicated by the accelerated stability figure. Aging of the oil, particularly in oxygenated heated environments, should be expected in prolonged storage.

Blends containing 25/75, 50/50, and 75 percent SFO/25 percent DF-2, along with neat sunflower oil, were tested in the two-cylinder engine. Engine test conditions were Notches 2, 4, 6, and 8 holding fuel mass flow rates constant at baseline values. The heating value of SFO was 13 percent less than DF-2 as mentioned above. As a result, the fuel energy consumption when operating on SFO at baseline fuel mass flow rates was 13 percent less than baseline. The elevated viscosity of the SFO required a 5 psi increase in fuel supply pressure to the filters to ensure adequate injector supply.

Brake horsepower decreased as the percentage of SFO in the blends increased at all notch positions as shown in Figure 7.17. The power reductions were primarily due to lower fuel energy consumption when operating on the SFO blends at baseline fuel mass flow rates. Cylinder pressure characteristics were comparable to baseline DF-2 and smoke levels were consistently below baseline values (Figure 7.18).

Brake thermal efficiency decreased as the percentage of SFO increased; the magnitude of the reductions for neat SFO are presented in Table 7.5. However, it was believed that the thermal efficiency reduction may have been due in part to operation at lower power levels. Therefore, a second sequence of tests was run using the same SFO blends as above at full baseline power (elevated fuel mass consumption) at each notch position to clarify this point. Thermal efficiencies again fell below baseline values, indicating that SFO did indeed reduce thermal efficiency. The reductions were much smaller at Notches 2, 4, and 6 (see Table 7.5), but were about the same at Notch 8 at 8 percent. The thermal efficiency reductions are believed to result, in part, from the increased viscosity of the sunflower oil causing reduced atomization of the fuel in the cylinder.

Table 7.4 Sunflower Oil/DF-2 Blends

Inspections	% Volume Sunflower Oil Blended With DF-2				
	0 Neat DF-2	25	50	75	100 Neat SFO
Cetane	49	44.8	43.8	42.2	37.0
API Gravity	37.7				21.7
Kinematic Viscosity cSt @ 40°C	2.54	4.86	9.05	16.02	31.93
Cloud Point, °F (°C)	-9	12.2 (-11)	17.6 (-8)	+	27 (- 3)
Pour Point, °F (°C)	0 (-18)	-7.6 (-22)	1.4 (-17)	1.4 (-17)	10 (-12)
Flash Point, °F (°C)	163 (73)	153 (67.2)	161 (71.7)	++	*628 (331)
Accelerated Stability (mg/100 ml)	1.0 est	1.76**	4.29**	13.76**	12.33**
Higher Heating Value (BTU/lb)	19,759	19,300	18,612	18,004	17,077
C, % wt	86.33				77.39
H, % wt	13.29				11.42
N, ppm	41				5
S, % wt	0.20 est				0
O, % wt (by difference)	0.19				11.19

est - estimated value, test not performed on this fuel
+ - unable to complete test, fuel too dark
++ - unable to complete test according to ASTM D93
* - Open cup flash point tester (ASTM D92) used for 100% SFO. All other flash points by closed cup (ASTM D93)
** - 100% SFO samples did not dry after two 30-minute drying periods using D2274 procedure.

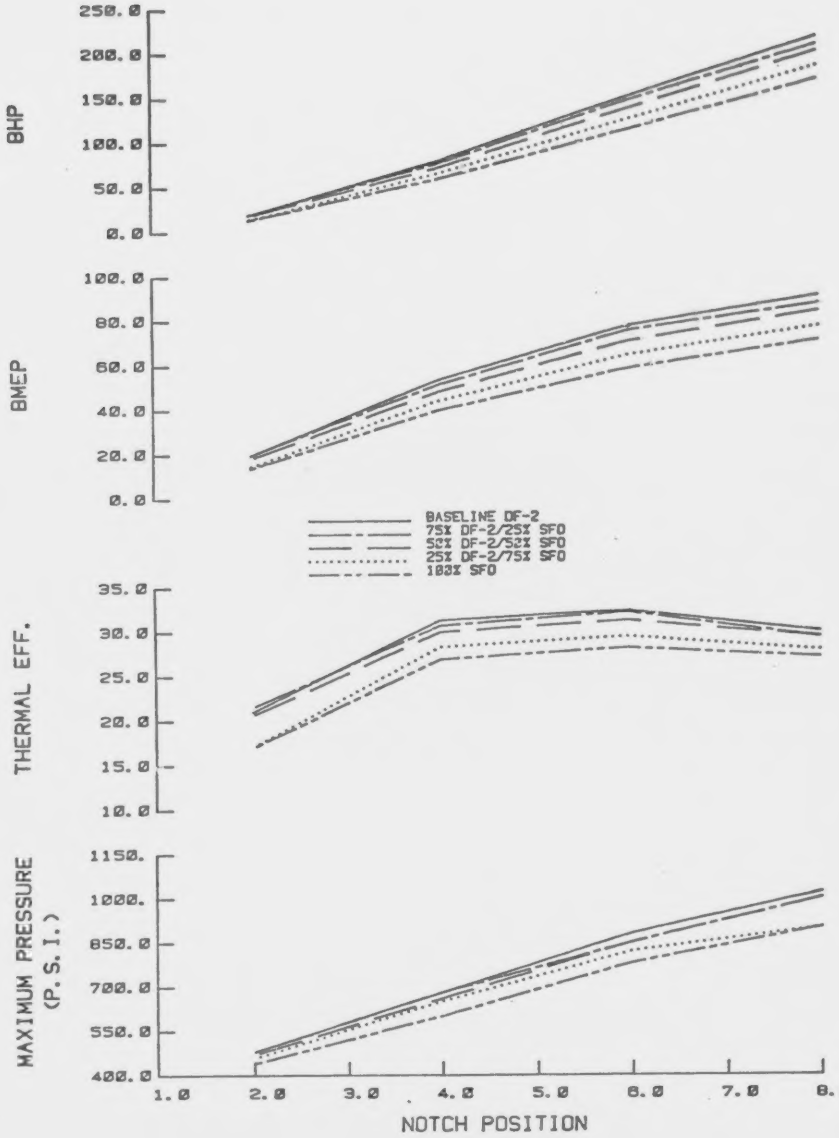


FIGURE 7.17 PERFORMANCE OF SUNFLOWER OIL/DF-2 BLENDS ON THE EMD 2-567B AT CONSTANT FUEL MASS FLOW RATES

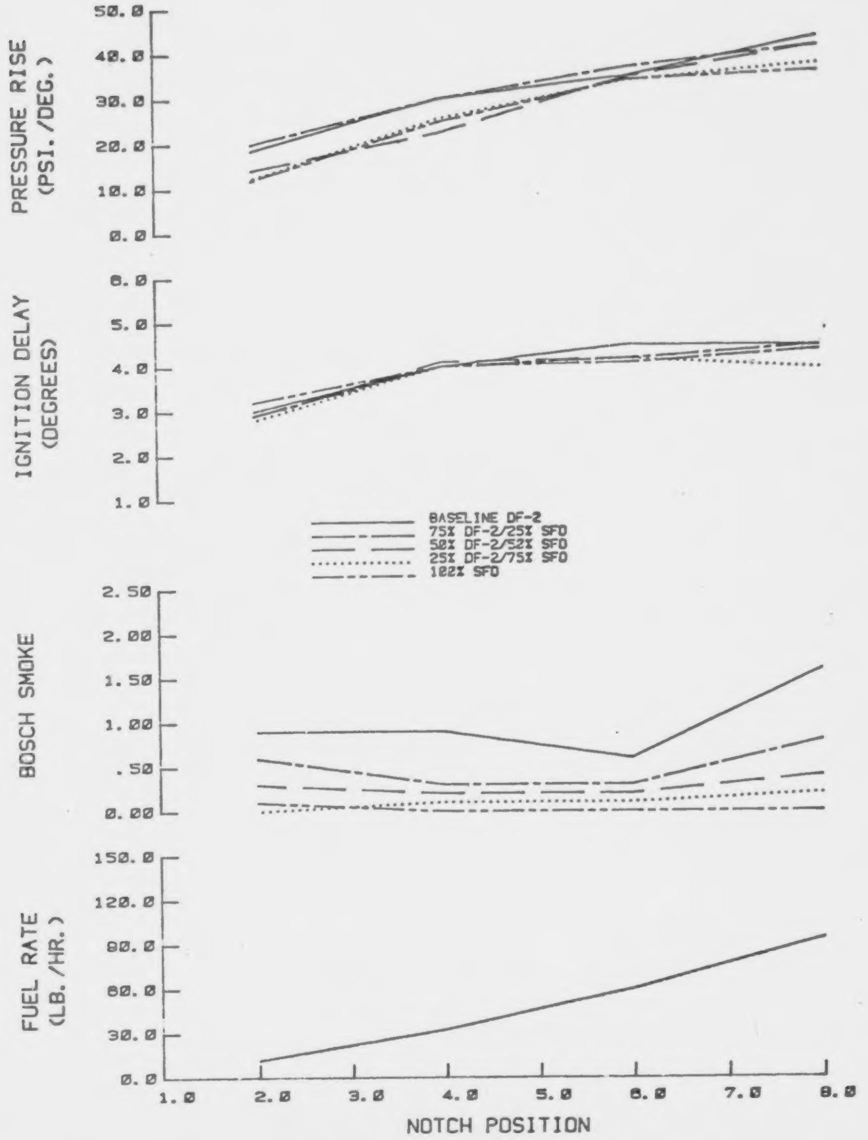


FIGURE 7.18 PERFORMANCE OF SUNFLOWER OIL/DF-2 BLENDS ON THE EMD 2-567B CYLINDER PRESSURE AND SMOKE CHARACTERISTICS, ENGINE OPERATED AT CONSTANT FUEL MASS FLOW RATES

Table 7.5 Reductions in Brake Thermal Efficiency
While Operating on Neat Sunflower Oil Relative to Baseline

Notch Position	SFO Fuel Consumption Equal to Baseline (% Reduction in Efficiency)	SFO Power Output Equal to Baseline (% Reduction in Efficiency)
2	21.1	3.4
4	15.1	6.2
6	13.9	6.1
8	10.1	8.3

Soft carbon trumpets formed on the injector tips, but these did not affect performance during these tests. However, deposits developed during extended operation, particularly at low power producing conditions, may, in fact, be an area of concern.

In general, engine operation on the sunflower oil blends and neat sunflower oil was quite good. Engine operation was stable and cylinder pressure characteristics were comparable to DF-2. Smoke levels were consistently at or below baseline values. Reduction in thermal efficiency was the only observed performance shortcoming. The engine was not operated for sufficient time to assess combustion chamber deposit effects.

One area of concern that remains with the sunflower oil is the potential dilution of the crankcase oil with sunflower oil. Polymerization of sunflower oil in the crankcase is likely. A sample of the two-cylinder crankcase oil was analyzed following the completion of all sunflower oil blends testing. Infrared spectroscophy indicated that less than .2 percent of the sunflower oil was present in the crankcase oil after approximately 80 hours of engine operation. At this time, the concentration of sunflower oil in the lubricating oil and the time and temperature needed to cause polymerization, and the adverse effects of polymerization, are unknown. These items will be addressed by a vegetable oil study at SwRI presently being conducted for the U.S. Department of Agriculture (USDA). In addition, the USDA program will investigate the effects vegetable oil refining has on vegetable oil properties and subsequent engine performance. The full range of vegetable oils at various stages of refining will be analyzed, then tested in a small diesel engine.

Storage problems could result because of instability of sunflower oil. Several of the vegetable oils, including soy and sunflower oil, are termed "drying" oils. That is, the oils will dry to form a varnish and, in fact, are used as the base for paints. Actual storage stability tests should be performed on neat SFO as well as SFO/DF-2 blends.

The results of the SFO tests indicate that vegetable oils with properties comparable to those tested in the two-cylinder engine can be substituted for diesel fuel. Long-term effects on deposits and lube oil contaminations need to be studied, but the problems do not look formidable. The vegetable oils are the second non-petroleum fuel investigated on this program that can replace diesel fuel without engine or fuel system modification, the first fuel being PARAHO DFM derived from shale oil studied during Phase II.

8. TEST RESULTS: TWELVE-CYLINDER ENGINE EXPERIMENTS

The following sections describe tests performed on the 12-cylinder EMD and GE engines. The purpose of such tests was to define the power output, thermal efficiency, combustion characteristics and smoke levels of candidate alternative fuels. Long-term effects such as wear, deposits, lube oil degradation and emissions were not addressed. Consequently, the engines were operated only for the short time that was required to gather adequate performance data. Precautions were taken to ensure that the engines were not adversely affected by a fuel, thereby minimizing maintenance and preventing degradation of baseline DF-2 performance. Engines were started, warmed up and performance checked at Notch 8 on DF-2. The fuel supply was then switched to the test fuel for the performance evaluation. At the completion of the test, the fuel supply was switched back to DF-2. The engine operated until the fuel system was fully purged of the test fuel and engine performance returned to baseline levels. Exceptions to this procedure are denoted in the following sections.

A total of five alternative fuels were tested in both of the 12-cylinder engines. These were alcohol/DF-2 emulsions, water/DF-2 emulsions, sunflower oil, blends of No. 6 fuel oil and DF-2, and high viscosity fuels. The latter item was not a test of a single fuel per se, but determined the fuel viscosity limits of the engines. The results of each of the test series are presented below.

8.1 HIGH VISCOSITY FUELS

The high viscosity fuel tests on the 12-cylinder engines were first attempted in he Spring of 1981 during Phase II. The purpose of these tests was to determine the naximum fuel viscosity that each of the engines could tolerate in their standard onfigurations. A full set of tests were completed on the EMD engine and the majority f the tests completed on the GE engine when problems with the fuel supply systems ere discovered. It was learned that the laboratory EMD engine utilized a different iel pump motor than common locomotives and employed a fuel pressure regulator ter this pump that the locomotives do not. The GE engine lacked a set of fuel filters, fuel strainer, and a fuel return pressure regulator. These discrepancies were sufficient to cause significant changes in the results of the high viscosity fuel tests. Data gathered prior to discovery of these problems indicated that the fuel supply system was the limiting factor in the use of a high viscosity fuel. The engine was unable to ingest sufficient fuel to maintain full power output above a specified viscosity at each fuel consumption rate. Thus, any changes in flow restrictions or supply pressure would affect the viscosity limit. Tests were discontinued at that time until the fuel systems could be modified to conform to common locomotive configurations.

Through consultation with EMD and GE, the necessary components were received and the discrepancies in the fuel systems corrected. It was also learned that there is no "standard" fuel system for these engines. The components used for various applications differ and these systems are periodically redesigned. Therefore, it should be stressed that the results obtained on high viscosity fuels are only relevant to the particular fuel systems on the laboratory engines. The conditions of the components in the system further compound the problem. For example, a worn fuel pump or clogged fuel filter will lower the viscosity limit. The results of the laboratory tests should be used only as a gauge of the range of viscosities that these engines might be expected to tolerate.

The test fuel for the high viscosity experiments was a lube stock, i.e., a petroleum product that is the base stock for lubricating oils. The lube stock possessed the desired viscosity range as well as a high cetane number and was relatively "clean" compared to other candidate high viscosity fuels, such as residual oils, which might cause filter plugging and soot formation. The properties of the lube stock are shown in Table 8.1. Fuel viscosity was varied independently of the other properties, with the exception of density, by heating the fuel before it entered the engine. The fuel viscosity values cited below were determined based on the fuel temperature measured just ahead of the final fuel transfer pump on the engine.

High Viscosity Test Results, GE 12-7FDL

The fuel viscosity limit of the GE engine increased greatly following modification of the fuel supply system primarily due to the addition of the fuel return backpressure regulator. Prior to modification, the fuel system was unable to pump sufficient fuel to the injectors to maintain power output on viscosities marginally over that of No. 2 diesel fuel. The underfueling limit was determined by observing reductions in engine power and fuel pressures. The backpressure regulator maintained a high fuel supply pressure to the injection pumps, preventing underfueling.

Table 8.1 Fuel Properties
High Viscosity Fuel Series

Kinematic Viscosity (cSt)	No. 2 Baseline Fuel	Lube Stock
40°C	2.54	79.75
100°C	—	10.13
Cetane Number	49.0	50.1
API Gravity @ 60°F	36.6	29.5
Higher Heating Value (BTU/lb)	19759	19693
Sulfur Content (wt %)	0.07	0.28
Distillation Range (° F)		
D86 or GC	D86	GC
IBP	357	484
10%	421	844
50%	494	939
90%	592	1123*
EP	640	1123

*Values greater than 1123°F exceeded the measurement capabilities of the test apparatus

Figure 8.1 shows the effect of viscosity on the injection pump fuel supply and return pressures. The fuel supply pressure rapidly increased as viscosity increased up to approximately 35 cSt, and continued to increase slowly beyond this viscosity at all notch positions. The fuel return pressure increased slightly between the baseline viscosity of 2.5 cSt and 35 cSt; above this range, the return pressure declined.

Figure 8.2 shows the effect of viscosity on brake horsepower and Bosch smoke. Brake horsepower decreased at Notches 2 and 4 as viscosity increased, but was essentially unaffected by viscosities of the range tested at Notches 6 and 8. The reduction amounted to 15 percent at 130 cSt and 5 percent at 60 cSt at Notches 2 and 4, respectively. Bosch smoke increased significantly at Notches 2 and 4, reaching a

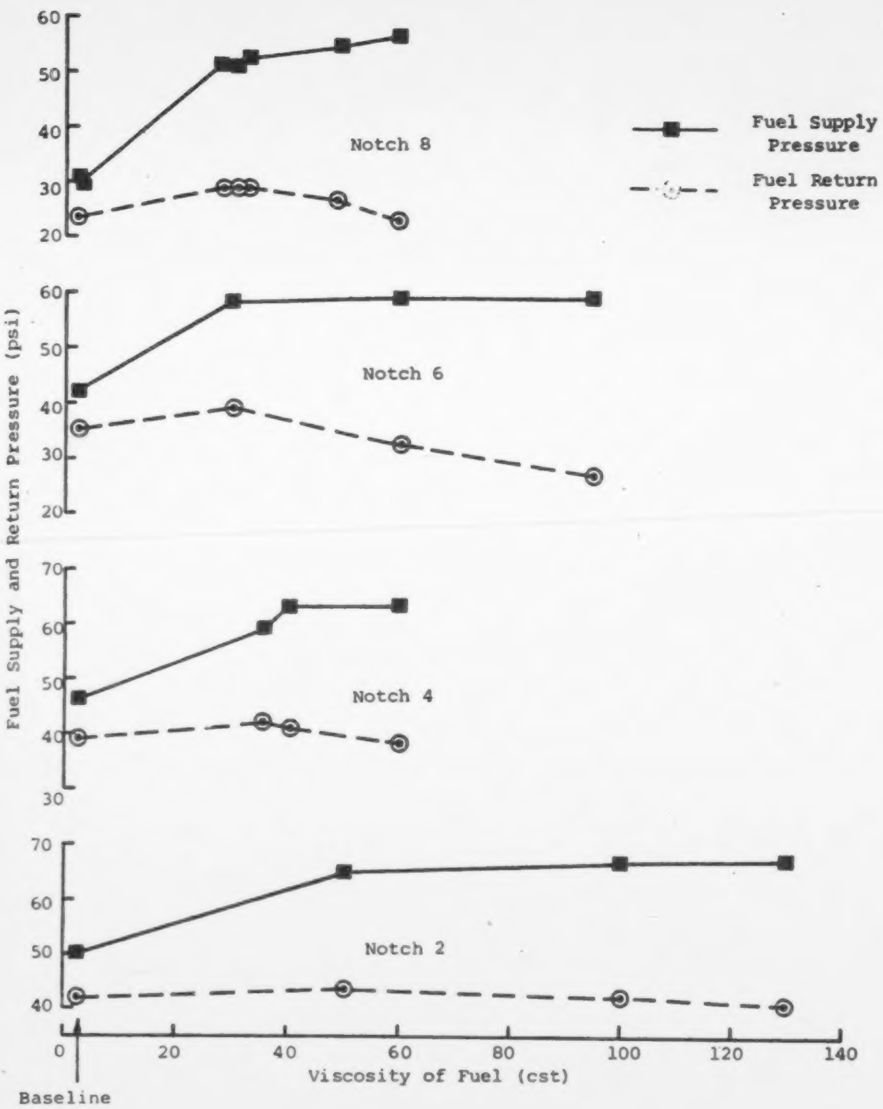


FIGURE 8.1 FUEL SUPPLY AND RETURN PRESSURE CHARACTERISTICS AS EFFECTED BY FUEL VISCOSITY, 12-CYLINDER GE ENGINE

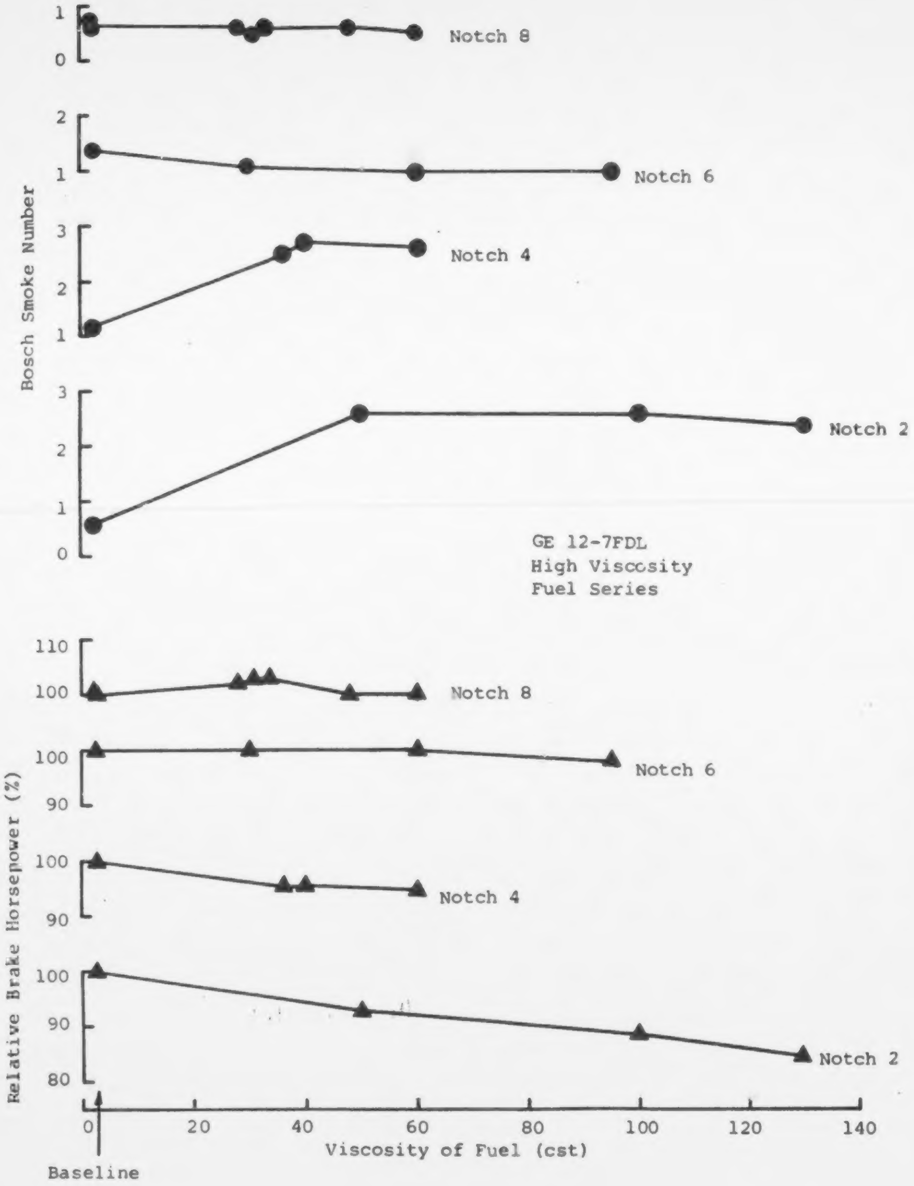


FIGURE 8.2 EFFECT OF FUEL VISCOSITY ON BHP AND SMOKE OF 12-CYLINDER GE ENGINE

maximum of Bosch 2.5 at about 35 cSt, the same viscosity at which fuel return pressure was highest. Smoke levels at Notches 6 and 8 were essentially unaffected by fuel viscosity.

The power reductions may have been the result of changes in the injection characteristics caused by the fuel viscosity and density variations. Viscosity affects the droplet size while density has a strong influence on spray penetration. Recall that the temperature of the fuel was varied to control the viscosity. As a result, both viscosity and density increased or decreased simultaneously. Likewise, both droplet size and spray penetration increased or decreased. The effects of increased droplet size and penetration are most obvious at low engine speeds where compression pressures and temperatures are relatively low and there is little turbulence to break up the fuel spray. Power reductions and increased smoke levels would be the natural outcome.

High Viscosity Test Results, EMD 12-645 E3B

Overpressuring the fuel supply system was the primary obstacle faced when operating the 12-cylinder EMD engine using a high viscosity fuel. Fuel supply pressure increased considerably with viscosity, as shown in Figure 8.3. The secondary fuel filter housing contains a pressure relief valve that bypassed fuel at 60 psi in case of filter clogging. Fuel supply pressure exceeded 60 psi at Notch 4, causing the seals around the sight glass bowls to leak. The pressure relief valve was incapable of bypassing sufficient fuel to maintain a constant 60 psi at high viscosities. Fuel pressure exceeded 60 psi at a viscosity of about 25 cSt. The pressures reached at high viscosities are not known since the pressure gauge was limited to 60 psi. Testing at Notch 4 was discontinued at a viscosity of 48 cSt where a constant drip from the sight glass bowl seal had developed. Overpressuring was not a problem at Notch 8, where the high engine fuel consumption rate kept the fuel supply pressure below approximately 60 psi.

The effects of viscosity on EMD brake horsepower and Bosch smoke number are presented in Figure 8.4 Brake horsepower at both Notches 4 and 8 decreased slightly as viscosity increased, the greatest reduction in each case being about 3 percent. Bosch smoke number was unaffected at Notch 8, but increased slightly at Notch 4. Notch positions below 4 were not tested, but they are expected to be more

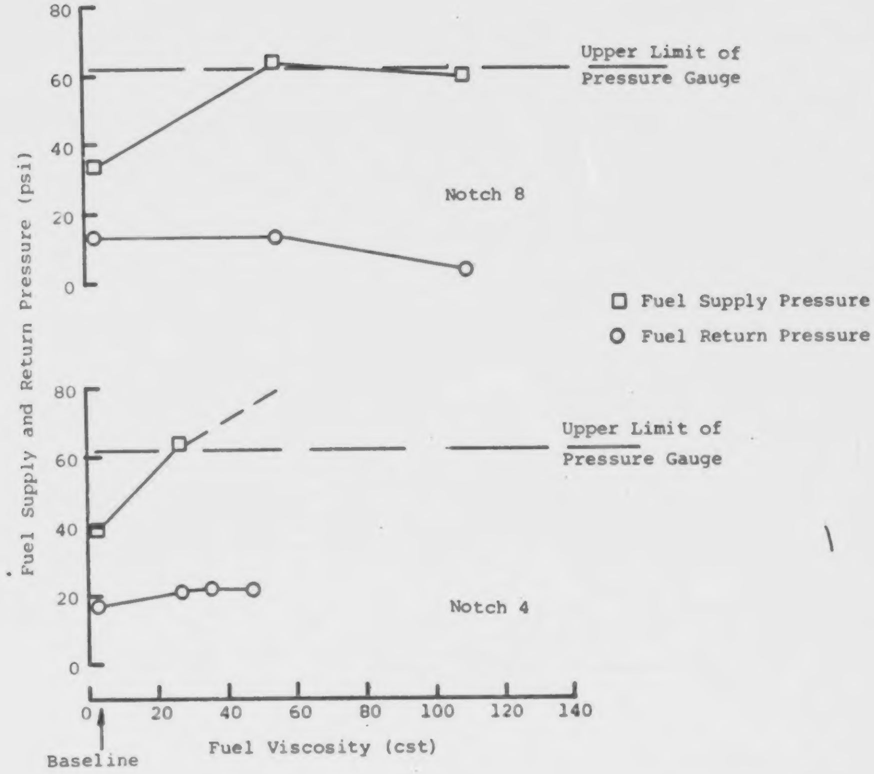


FIGURE 8.3 FUEL SUPPLY AND RETURN PRESSURE AS AFFECTED BY FUEL VISCOSITY, 12-CYLINDER EMD ENGINE

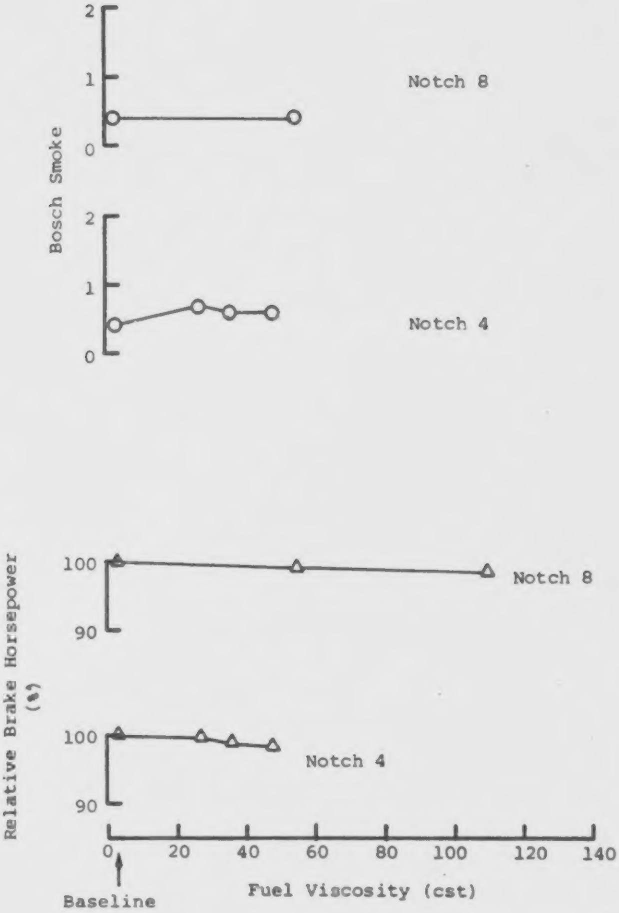


FIGURE 8.4 EFFECT OF FUEL VISCOSITY ON BHP AND SMOKE OF 12-CYLINDER EMD ENGINE

sensitive to changes in fuel viscosity than the upper notches as was the case with the GE.

The majority of the difficulties encountered during the course of the high viscosity tests on the EMD and GE engines were related to the fuel transfer and injection systems. Combustion abnormalities were evident at low notch positions which were suspected to result from altered injection characteristics. It did not appear that combustion was a problem above Notch 6. The limitation at the upper notches on the GE was the ability to pump sufficient fuel to completely fill the injection pumps. This could be overcome by supplying the fuel at higher pressure. A maximum viscosity of 110 cSt was tested on the EMD at Notch 8; this was the highest viscosity (lowest fuel temperature) that the fuel system could supply without adding a cooling circuit to further reduce the fuel temperature.

The fuel supply difficulties can be overcome by redesigning the fuel supply system for the desired viscosity range. However, there still exists a fuel viscosity limit above which combustion abnormalities will become a problem. The combustion limited viscosities should be defined for the entire operating schedule. The use of a high viscosity fuel can then be tailored to the notch positions that can tolerate the fuel. Redesign of the injectors might stretch the combustion limited fuel viscosity further. However, it is likely that viscosity will not be the fuel property that limits the use of a heavy fuel (see Section 6.1) and injector redesign should not be considered until maximum expected viscosity is defined.

8.2 UNSTABILIZED ALCOHOL-IN-DF-2 EMULSIONS

The use of alcohols as alternative fuels for medium-speed diesel engines in the form of emulsions with DF-2 were studied during Phase II. Both methanol and ethanol were tested in the two-cylinder EMD in stabilized and unstabilized emulsions. These tests were extended to the 12-cylinder engines in Phase III.

Testing alcohol-in-diesel fuel emulsions presents several problems. Methanol and ethanol (except anhydrous ethanol) are not soluble in DF-2. Anhydrous ethanol can be put into solution with diesel fuel but separation occurs if ethanol contains more than

0.5 percent volume water. Both ethanol and methanol can be emulsified with diesel fuel in either stabilized or unstabilized form. The stabilized emulsions require a large volume of a chemical stabilizer to prevent separation of the alcohol and DF-2. This volume is roughly equal to the volume of alcohol present. Unstabilized emulsions do not require the chemical stabilizers, but they will separate and therefore must be emulsified immediately before injection into the engine. Further, because alcohols possess only about one-half or less of the volumetric energy of DF-2, injector output must be increased to deliver full power when operating on an emulsion or solution of high alcohol content.

The amount of alcohol that can be consumed in an emulsion is limited by engine knocking. The alcohols are extremely low cetane number products (calculated cetane numbers based on octane numbers are 4 and 5 for methanol and ethanol, respectively). The cetane number of an emulsion is proportional to the volume content of alcohol and diesel fuel.

The results of the two-cylinder engine experiments were reviewed for guidance in planning full-size engine emulsions tests. The conclusions drawn from the two-cylinder engine experiments were:

1. The maximum alcohol content of the emulsion may be limited by the injection pump capacity at high power producing conditions due to the low volumetric heat content of the alcohol.

2. Engine knock levels increase in proportion to the quantity of alcohol in the emulsions. The knock limited percentage of alcohol content is generally higher in the lower notch positions. Up to 40 percent volume alcohol was tested in the lower notch positions, but only 30 percent could be consumed at rated speed and load.

3. Increases in thermal efficiency were obtained at the lower notch positions while operating on the unstabilized emulsions, but slight reductions in efficiency were noted in the upper notch positions.

4. Large quantities of a chemical stabilizer are required to produce stabilized emulsions of either methanol or ethanol in DF-2. The volume of stabilizer is roughly equal to the volume of alcohol present. Thermal efficiency of stabilized emulsions is poor by comparison to the unstabilized emulsions as well as baseline DF-2.

The unstabilized emulsions were selected for full-sized engine testing based on the above conclusions. The objectives of the full-sized engine tests were:

1. To define the modifications necessary to convert the full-sized engines to operate on unstabilized alcohol and DF-2 emulsions.
2. To determine the maximum alcohol content that can be consumed in an unstabilized emulsion with DF-2.
3. To determine the effects of the emulsions on engine performance and combustion characteristics.

An on-line emulsifying system was designed for the 12-cylinder engines based on experience gained during the two-cylinder engine experiments. This system is described in detail below. The engines were started, warmed up, and performance was checked on baseline DF-2. Alcohol was then metered into the fuel loop in the desired proportion. The quantity of alcohol in the emulsion was incrementally increased until either engine knocking or injection pump capacity limits were reached. At the completion of a test, the alcohol supply was shut off and the engine was run for sufficient time on DF-2 to fully purge the fuel loop of alcohol.

All tests were conducted on an equivalent BTU basis. That is, the combined BTU input from alcohol and DF-2 was equal to the BTU input of baseline DF-2 for the same notch position. Since the engine was always receiving the baseline heat input, any change in engine power output relative to the baseline level was a direct indicator of an increase or decrease in thermal efficiency. Also, since the volumetric heat content of the alcohols was significantly less than that of diesel fuel, the total volume of emulsion injected per stroke was necessarily greater than that of neat DF-2 to maintain the same total heat input.

On-Line Emulsifying Fuel System

The alcohol-in-DF-2 (and later the water-in-DF-2) emulsions tested on the 12-cylinder engines were mixed on-line. The two fuel components were pumped from separate storage containers to the engine where they were proportionally mixed, then emulsified immediately before consumption. A schematic of this system is shown in Figure 8.5. The emulsifier was a Hydroshear designed and constructed by Ontario Research. Referring to the schematic, the two components were initially mixed in a "tee", then pumped to a small day tank. The day tank served as a central point in the system into which supply fuel and return fuel from the injectors were led, and from which injector supply fuel was drawn. Its primary functions were to nullify pressure surges and remove gases from the return fuel, helping to maintain a steady flow rate through the Flo-tron for an accurate fuel consumption measurement.

The Hydroshear emulsifier was mounted on the engines as close to the injectors as was possible. The normal engine fuel filters were removed. Alcohol and DF-2 were filtered before mixing. The volume of fuel contained in the fuel loop was minimized by using the shortest possible flow path to minimize the possibility of emulsion separation. As a result, the time required to change the volume ratio of the components in the emulsion was very short (10 to 15 minutes).

The Hydroshear emulsifier (see Figure 8.6) has no moving parts and is operated by hydraulic pressure. The emulsion enters the Hydroshear tangentially and must swirl to the center of the chamber before it can exit through orifices. The emulsion is sheared as it passes from the outer edge of the chamber to the center by velocity gradients.

The rack positions of the EMD and GE engines were adjusted for maximum fuel volume delivery. In both cases, the adjustment would permit operation at the physical limit to rack travel. A significant portion of alcohol could then be tested in the upper notch positions.

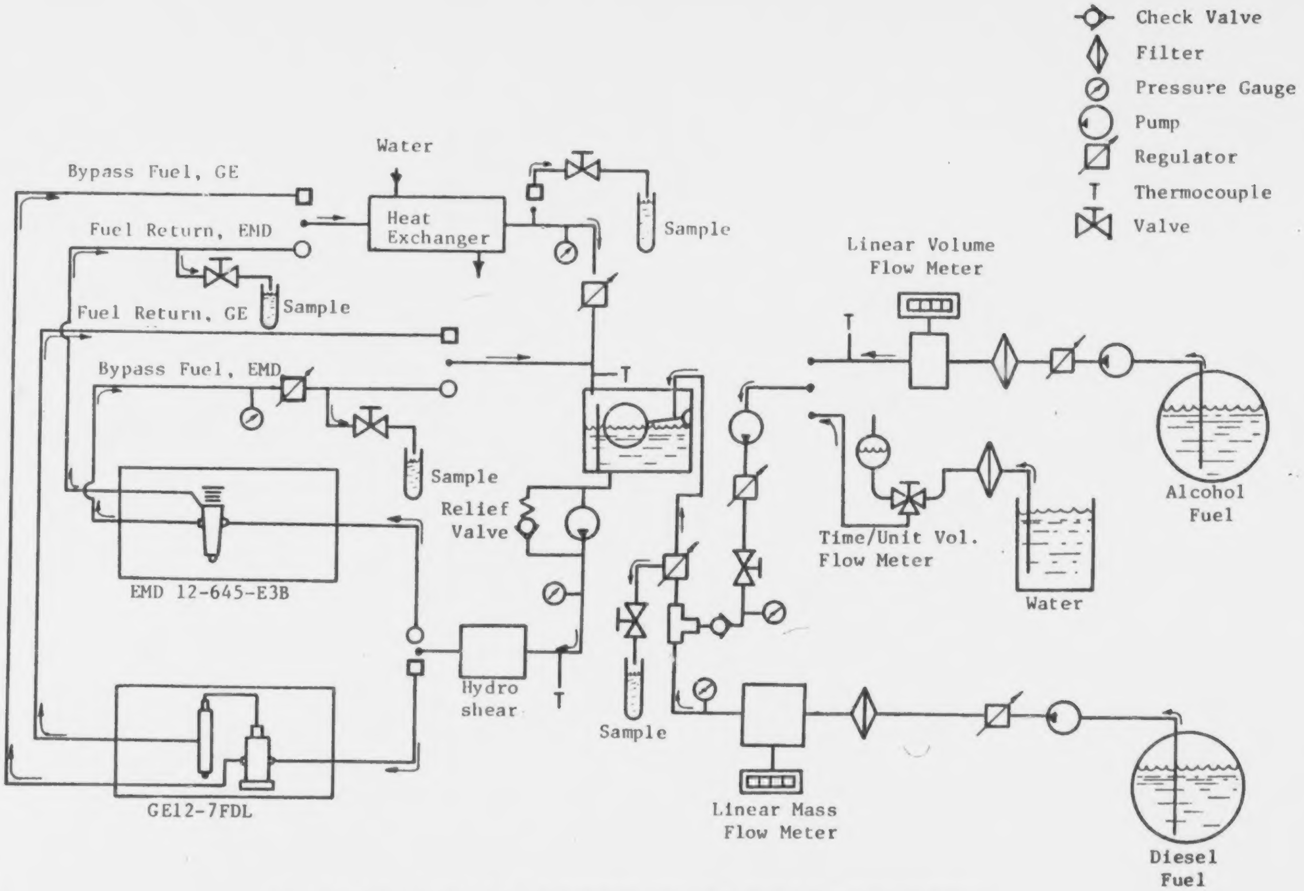


FIGURE 8.5 12-CYLINDER ENGINE ON-LINE EMULSIFYING SYSTEM

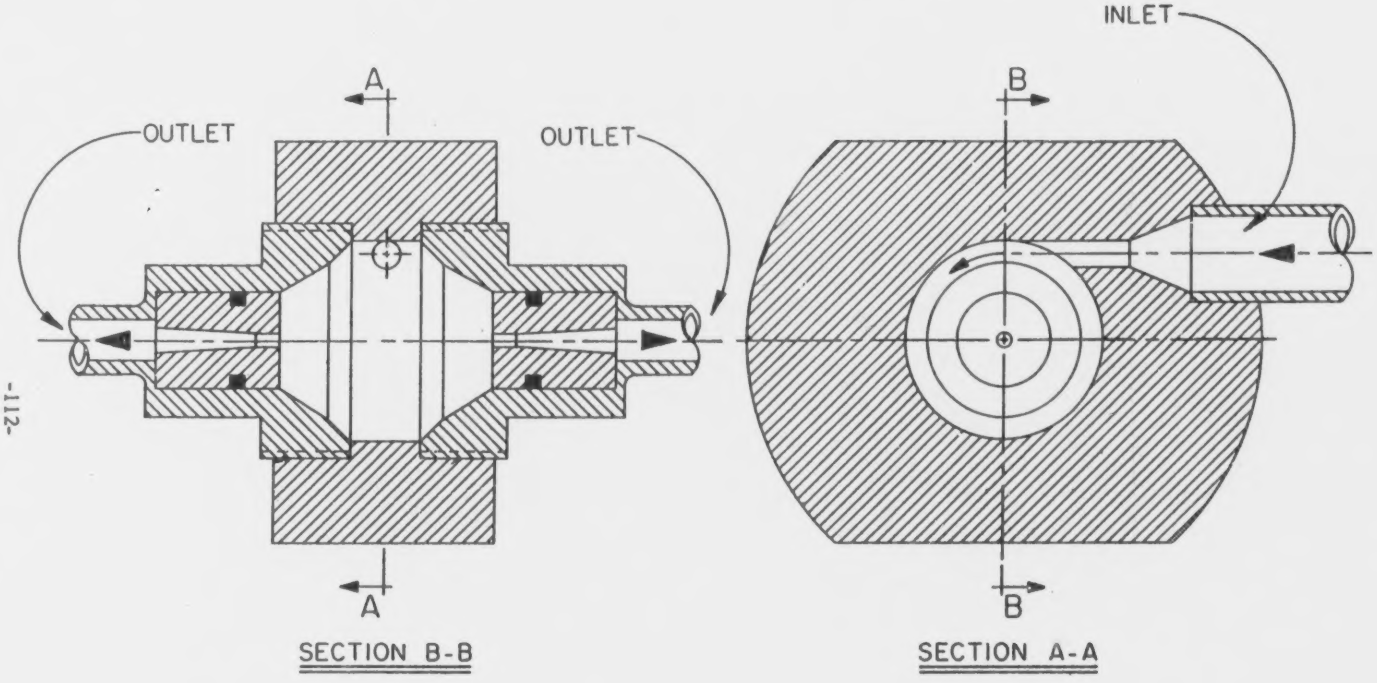


FIGURE 8.6 HYDROSHEAR EMULSIFIER ASSEMBLY

Alcohol Emulsion Test Results

Qualitatively, the results of the tests on both 12-cylinder engines were much improved over those of the two-cylinder EMD. Twelve-cylinder engine operation was much more stable; i.e., cyclic variations as gauged by changes in audible combustion noise and the cylinder pressure traces were very low. The performance data were very repeatable. These improvements were attributed to the very good quality of emulsions. Quality was gauged by the appearance of the emulsion and the time required for separation of the alcohol and DF-2. The emulsions produced during two-cylinder engine experiments began to separate almost immediately after a sample was drawn from the fuel loop and reached full separation within approximately one hour. Droplets of alcohol and DF-2 were visible immediately upon sampling. By contrast, the emulsions produced by the Hydroshear were milky white by appearance, and it was very difficult to discern droplets without magnification. Several minutes were required before droplets were visible, and the two components would not fully separate if allowed to stand. Centrifuging was attempted to speed separation, but the emulsion did not fully separate. Ethylene glycol (which is used to separate ethanol from gasohol) was mixed with the alcohol emulsion, and then centrifuged. Full separation would occur if 10 percent volume ethylene glycol were mixed with an emulsion sample.

Performance of the EMD and GE engines at Notch 8 was nearly identical (see Figures 8.7 and 8.8). The amount of alcohol that each engine could consume at Notch 8 was limited by the output of each injection system. The unit injectors restricted the EMD alcohol consumption to between 15 and 20 percent volume. The GE achieved a maximum of 25 percent alcohol. These high alcohol volumes were possible only through adjustment of the injector racks to achieve maximum volume delivery. Thermal efficiency of both engines was at or slightly above the DF-2 value at all emulsion ratios tested at Notch 8.

Performance of the alcohol emulsions at the lower notch positions differed greatly between the engines. The emulsions produced very high white smoke levels and poor thermal efficiencies at Notch 2 on the GE. The situation greatly improved at Notch 4 with smoke and thermal efficiency equalling baseline DF-2. By contrast, slight thermal efficiency improvements were noted at several emulsion ratios at Notches 2

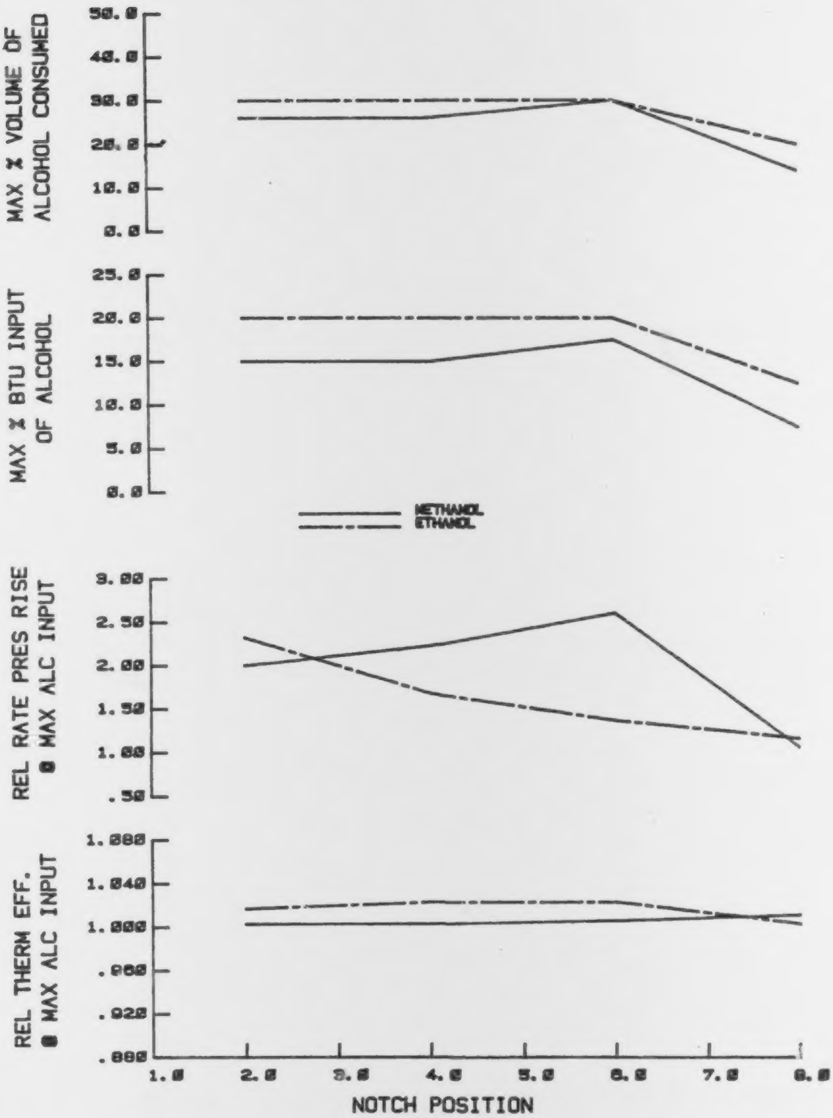


FIGURE 8.7 KNOCK-LIMITED ALCOHOL INPUT OF THE EMD 12-645 E3 ENGINE USING UNSTABILIZED EMULSIONS

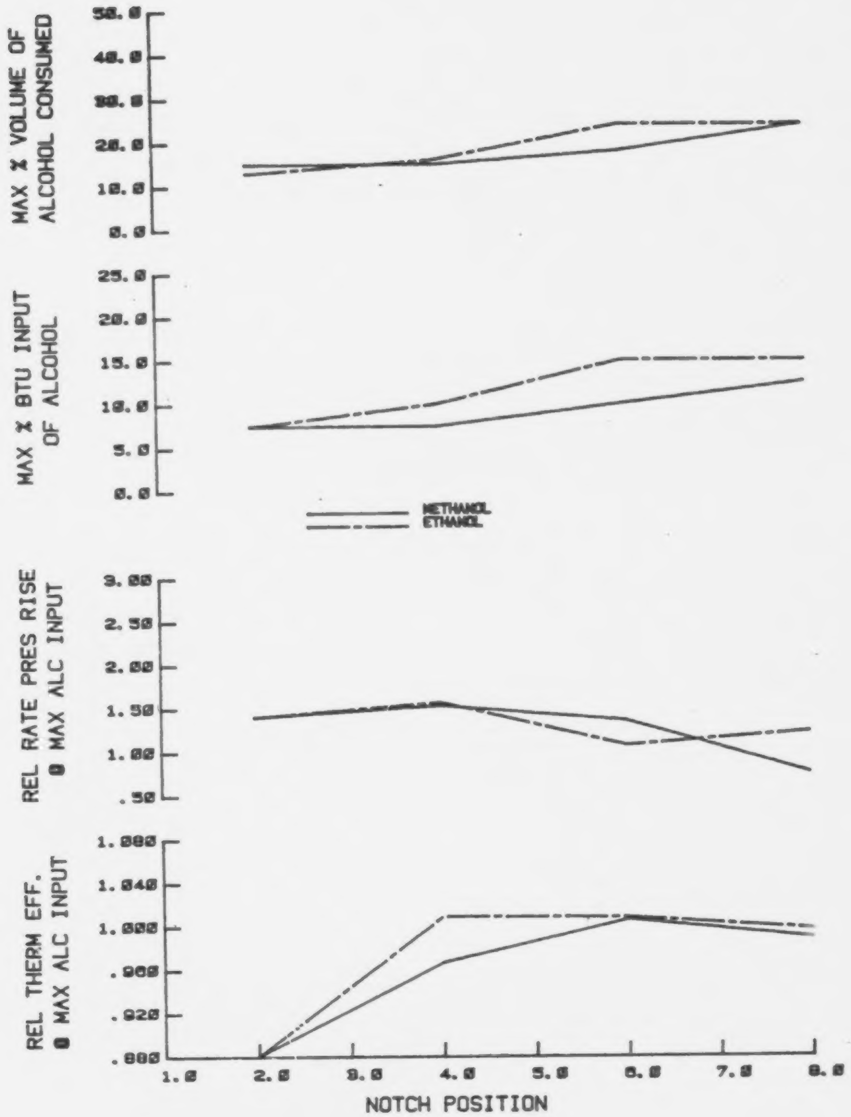


FIGURE 8.8 KNOCK-LIMITED ALCOHOL INPUT OF THE GE 12-7FDL ENGINE USING UNSTABILIZED EMULSIONS

and 4 with the EMD. The poor performance of the GE engine at Notches 2 and 4 was believed to result from a very rich fuel environment created by the relatively large volume of emulsion injected. The exhaust gas energies were not sufficient to drive the free-wheeling GE turbocharger at Notches 2 and 4, and essentially no intake air boost pressure was generated. The EMD turbocharger was mechanically driven at these positions to provide scavenging air flow. The performance plots for the methanol and ethanol unstabilized emulsion experiments are presented in Appendix D.

The combustion characteristics of the engines while operating on alcohol emulsions are essentially identical to those reported for the two-cylinder EMD engine (see Phase II Final Report). The ignition quality (cetane number) of the emulsions decreased as alcohol content increased resulting in increased ignition delay and rate of pressure rise. The maximum alcohol concentrations tested were 30 percent volume at Notches 2 through 6 and 20 percent at Notch 8 on the EMD, and ranged from 12 percent at Notch 2 up to 20 percent at Notch 8 on the GE. Slight knocking became evident at alcohol contents that were approximately one-half of the maximum values tested. The knock limited inputs were determined subjectively by the engine operators based on audible combustion noise as well as the cylinder pressure trace. Rates of pressure rise were typically 1.5 to 2.5 times that of baseline DF-2 at the maximum alcohol concentrations tested.

The knock limited inputs of methanol and ethanol were very nearly equal on a volume basis. This is to be expected since the limit was a function of the emulsion cetane number, which is proportional to the volume content of alcohol. Since methanol contains approximately 15 percent less energy (on a mass basis) than ethanol, the percentage of DF-2 energy input that can be replaced by methanol was significantly less than that of ethanol.

Thermal efficiencies were at or above baseline values with the exception of Notch 2 on the GE. The increases in thermal efficiencies did not amount to more than approximately 2 percent on either engine. Smoke levels were at or below baseline values, again with the exception of the high white smoke levels observed from the GE at Notches 2 and 4.

Further work is needed in the areas of wear, durability, and exhaust emissions before the alcohol emulsions should be considered for extensive use. On-board fuel system modifications should be studied for each application as well as the dual tankage needed for the alcohol and DF-2. If operation on high alcohol percentages is desired, higher output injection systems will be needed to accommodate the emulsions.

8.3 WATER/DF-2 EMULSIONS

The objective of this task was to evaluate the potential for water/DF-2 emulsions to reduce specific fuel consumption and exhaust smoke levels below levels normally measured when operating the 12-cylinder laboratory engines on DF-2. Researchers have documented reductions in these two parameters as well as in exhaust emissions when various engines have been operated on water emulsions. However, the results are very inconsistent; apparently, each type of engine responds differently to the water emulsions. It has thus far been impossible to predict the effects of the emulsions on engine performance; actual engine tests are necessary to determine if improvements are possible. Reference 20 contains a discussion on the theorized reasons for these reductions plus a bibliography on emulsions programs.

The Hydroshear on-line emulsifying system developed for production of alcohol-in-DF-2 emulsions (see Section 8.2) was installed for the water emulsions tests. Minor modifications were made to the fuel supply circuit to consume city tap water (see Figure 8.7), but the system was unchanged otherwise. A wide range of water contents were evaluated. A constraint placed on the test was that the DF-2 consumption rates be held constant at the baseline values. In this manner, any changes in Bhp, thermal efficiency, or BSFC would be attributable solely to the water emulsion, not to changes in engine power due to altered DF-2 consumption. Also, the total volume of fuel injected per stroke would increase in proportion to the amount of water emulsified into the DF-2. The injector racks were adjusted for maximum possible fuel delivery to permit operation using high water percentages in the upper notches.

Water concentrations were determined during engine tests by measuring the DF-2 and water flow rates. Emulsion samples were drawn from several points in the fuel loop to check the quality of the emulsions. The samples provided a rough estimate of the water concentration, but were not relied upon for an accurate concentration because of the experiences with poor separation of the alcohol emulsions (see Section 8.2).

The water emulsion tests were performed in two sequences. The first sequence investigated water concentrations ranging from 5 to 30 percent volume. The second sequence of experiments evaluated water concentrations in the range of 1 to 5 percent volume. The data acquired during this second sequence were monitored by a low-speed computer data acquisition system for increased precision of engine power output and fuel consumption measurements since the initial sequence indicated that the performance changes were quite small.

Water Emulsion Test Results, 12-Cylinder EMD Engine

The performance results for the water emulsions tests on the EMD engine are presented in Figure 8.9 and 8.10. Tests were performed in the even numbered notch positions only. A maximum of 30 percent volume water was tested in Notches 2, 4, and 6. Water input was limited by injector capacity to approximately 10 percent at Notch 8.

Reductions in brake specific fuel consumption (BSFC) were observed at all tested notch positions (Figure 8.9); the reductions were greatest in the lower notches. BSFC decreased by a maximum of 2.5 percent at Notch 2. This was the only tested notch position at which BSFC decreased at high water concentrations, i.e., in excess of 15 percent volume. The largest reductions in BSFC at Notches 4 and 6 occurred at 5 percent volume water and amounted to approximately 2 and 1 percent, respectively. BSFC was approximately equal to if not greater than the baseline value at water concentrations above the 5 percent range at these two notches. Reductions in BSFC at Notch 8 were very slight, amounting to less than 0.5 percent, which is the level of repeatability of BSFC at Notch 8.

Under the constraint of these tests (that the DF-2 consumption rate be held constant at baseline values regardless of water content) brake mean effective pressure, brake horsepower, and brake thermal efficiency varied in proportion to the changes in

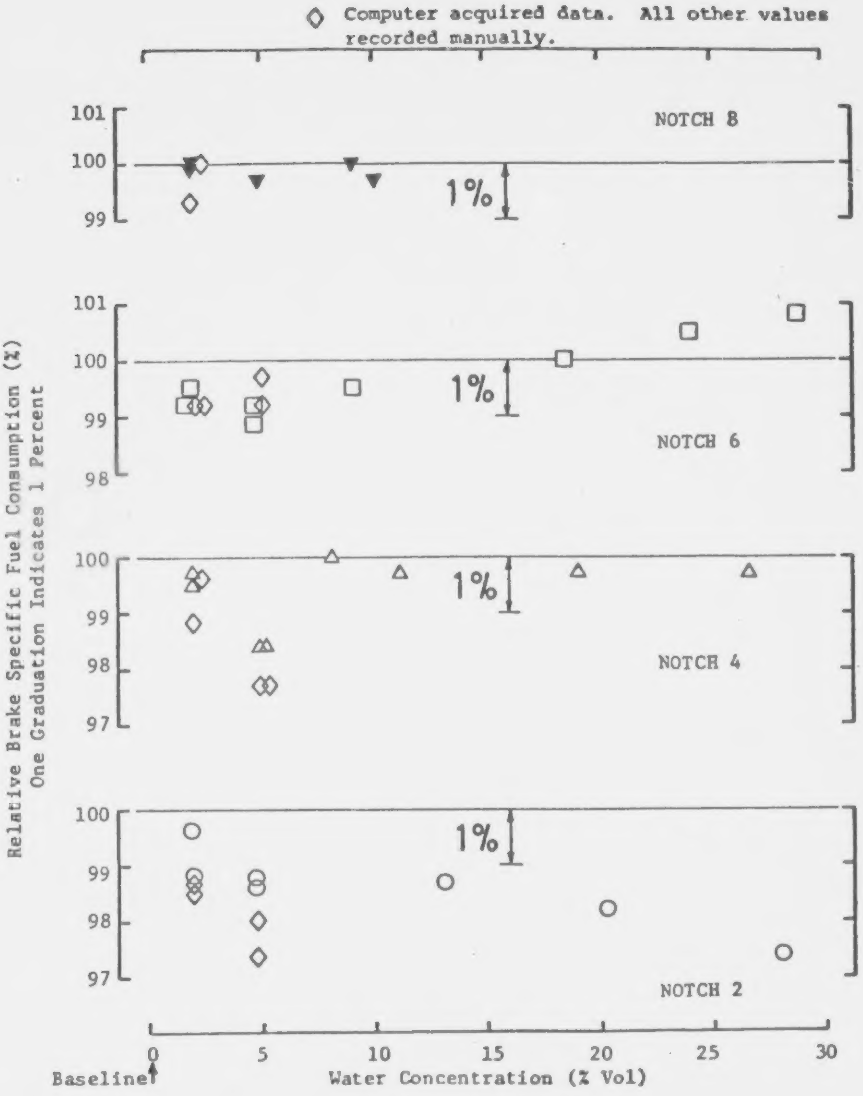


FIGURE 8.9 EFFECT OF WATER EMULSIONS ON BRAKE SPECIFIC FUEL CONSUMPTION, EMD 12-645 E3 ENGINE

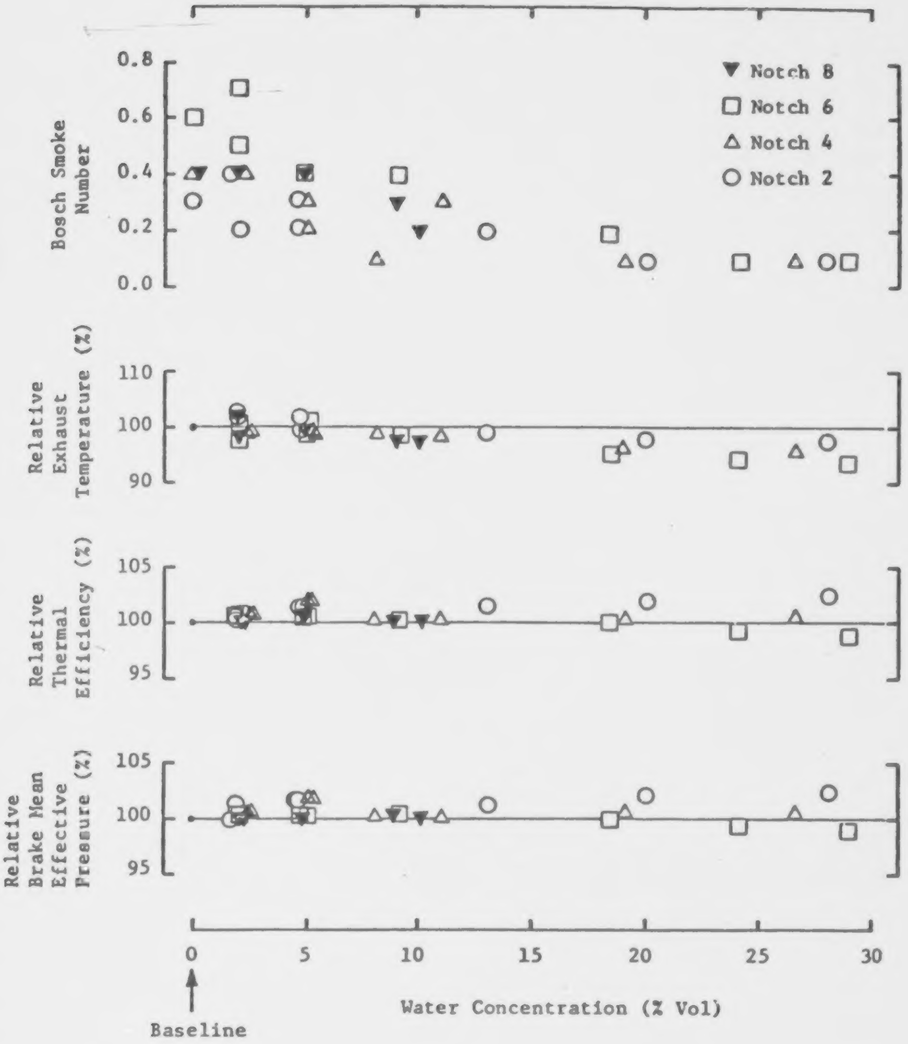


FIGURE 8.10 EFFECTS OF WATER EMULSIONS ON EMD 12-645 E3 ENGINE PERFORMANCE

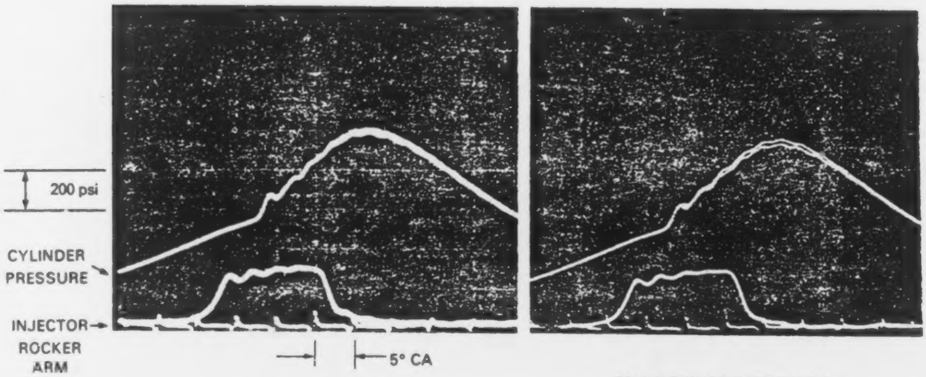
BSFC. For example, a 2 percent improvement (reduction) in BSFC is also indicative of a 2 percent improvement in thermal efficiency, Bhp, and BMEP.

Reductions in exhaust temperature and Bosch smoke levels were recorded at all notch positions (Figure 8.10). Smoke levels at Notches 2, 4, and 6 decreased from baseline values ranging from .3 to .6 to approximately 0.1 at water concentrations over 20 percent volume. Exhaust temperature reductions of 3 to 6 percent were observed for these same notches at high water concentrations.

The cylinder pressure data were analyzed to determine the effects of the water emulsions on injection and combustion characteristics. These data are presented in Appendix E. The water acted as a cetane number depressant; that is, the addition of water increased the ignition delay period and subsequently the rate of pressure rise and peak cylinder pressure. The effects on the ignition characteristics were sufficient to cause approximately a 60 percent increase in rate of pressure rise at Notch 6 at a water concentration of 29 percent, and approximately a 40 percent increase at Notch 2 with 28 percent water. Peak cylinder pressure increased by a maximum of 10 percent at these high water concentrations. Start of combustion occurred at approximately the same timing regardless of water content. The advance in injection timing that resulted from injection of a larger volume of fuel was approximately equal to the increased time required for the ignition delay, resulting in a constant start of combustion. These effects can be seen on the cylinder pressure traces for Notch 4 operation presented in Figure 8.11.

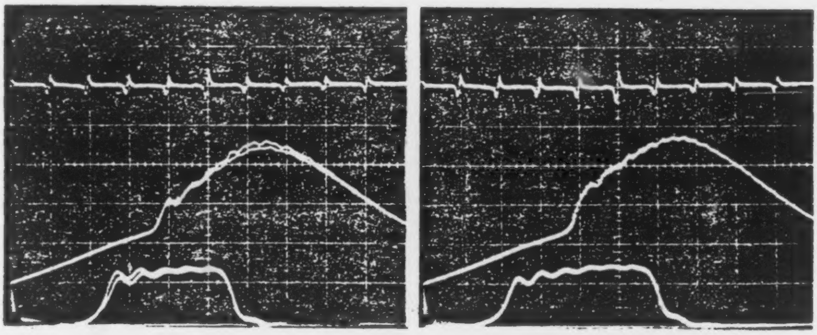
Water Emulsions Test Results, GE Engine

Water emulsions tests were performed on the GE engine under the same constraints placed on the EMD test series. The performance data for the General Electric water emulsions tests are presented in Figure 8.12 and 8.13. The injection pump capacity limited the Notch 6 water concentration to a maximum of 19 percent, and that of Notch 8 to 7 percent. Slight improvements in BSFC were noted at Notch 8; the reductions amounted to 0.5 percent in the range tested, i.e., between 2 and 7 percent volume water. BSFC at Notch 6 was essentially unchanged in this same range of water concentrations, but a 1 percent reduction was noted at 19 percent volume



BASELINE DF-2

5% WATER/DF-2 EMULSION



11% WATER/DF-2 EMULSION

, 27% WATER/DF-2 EMULSION

FIGURE 8.11 EFFECT OF WATER EMULSIONS ON EMD 12-645 E3 CYLINDER PRESSURE CHARACTERISTICS, NOTCH 4

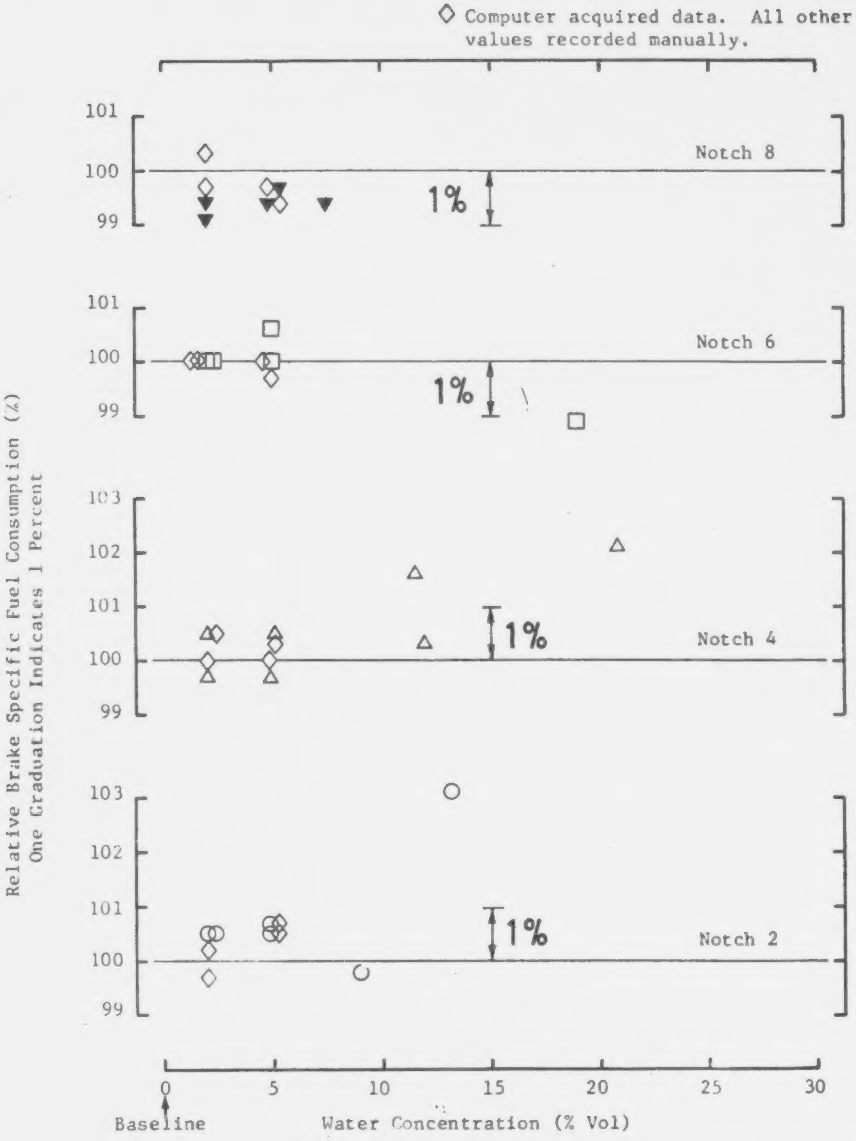


FIGURE 8.12 EFFECT OF WATER EMULSIONS ON BRAKE SPECIFIC FUEL CONSUMPTION, GE 12-7FDL ENGINE

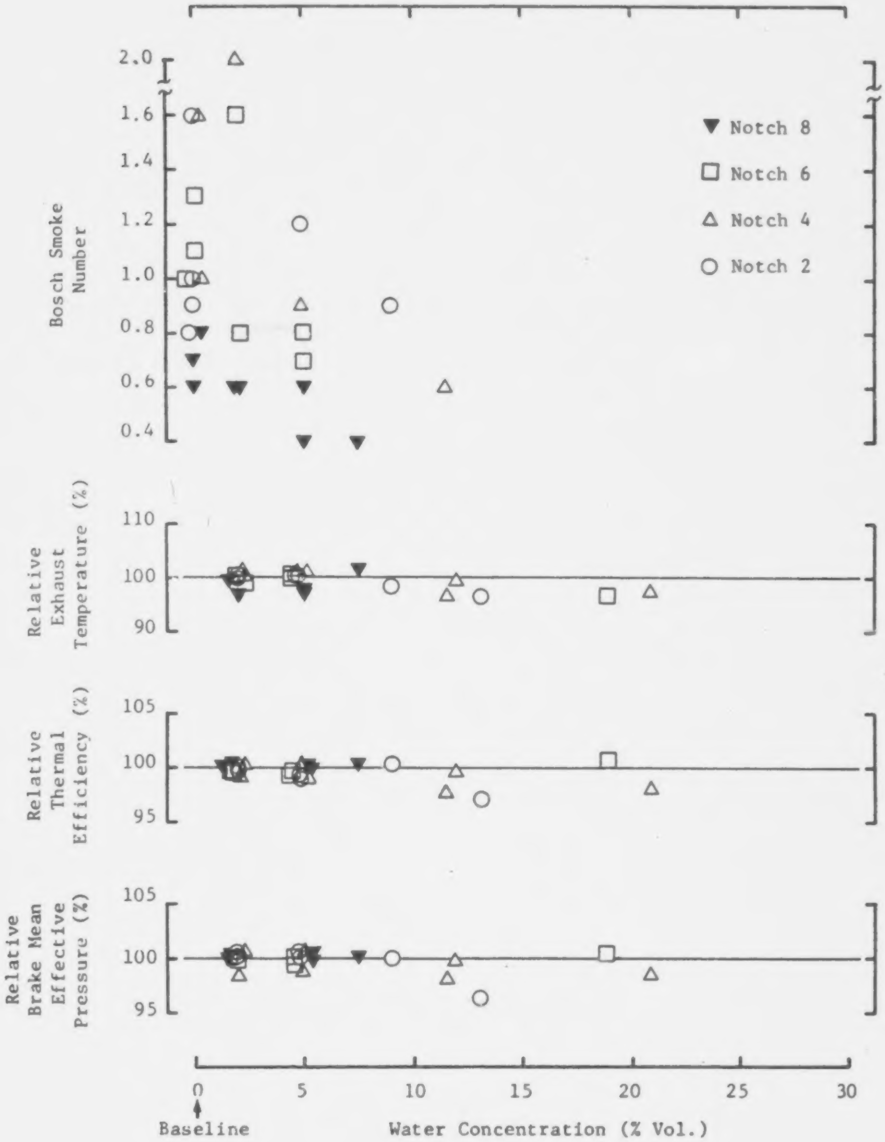


FIGURE 8.13 GE PERFORMANCE USING WATER/DF-2 EMULSIONS

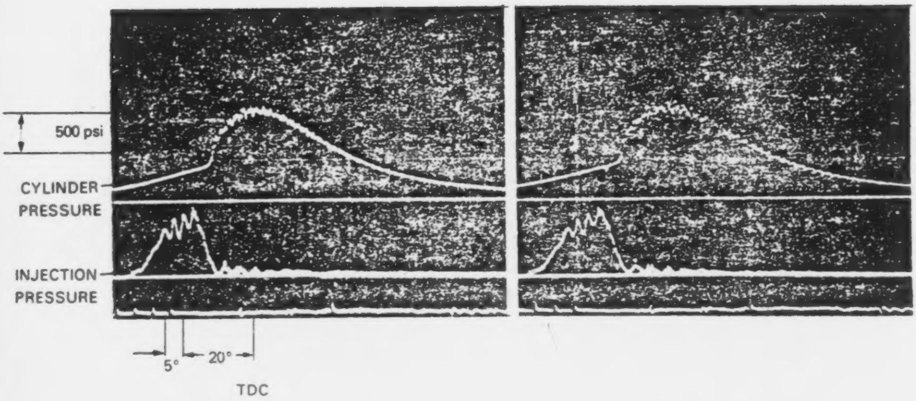
water. The water emulsions had an adverse effect on BSFC in almost all cases at Notches 2 and 4. Increases in BSFC ranging from 0.5 to 3.0 percent were recorded. These trends are quite similar to those reported for the alcohol-in-DF-2 emulsions in Section 8.2.

The Bosch smoke data (Figure 8.13) exhibited an unusually large amount of scatter. Smoke levels decreased slightly at Notch 8 as water content increased, reaching a minimum value of 0.4. The smoke data at the remaining notches was inconclusive, but increases in smoke are not expected to be a problem. White smoke, which is not detected by the Bosch method, was not evident at any of the notch positions. White smoke was generated at the lower notch positions when operating on the alcohol-in-DF-2 emulsions and the same was expected of the water emulsions. Slight reductions in exhaust temperatures, amounting to 2 or 3 percent, were noted at all notch positions.

The effects of the water emulsions on the combustion characteristics of the GE were quite similar to those of the EMD. The GE data are presented in Appendix F. Ignition delay increased with water concentration, resulting in significant increases in rate of pressure rise. The General Electric injection system employs a constant start of injection; as a result, increases in ignition delay caused by the emulsions retarded start of combustion. Rate of pressure rise increased by as much as 70 percent at the maximum water concentrations tested at Notches 2, 4, and 6. The reverse was true at Notch 8 where a 10 percent reduction in rate of pressure rise was seen when consuming 7 percent volume water. The emulsions had very little effect on the peak cylinder pressures.

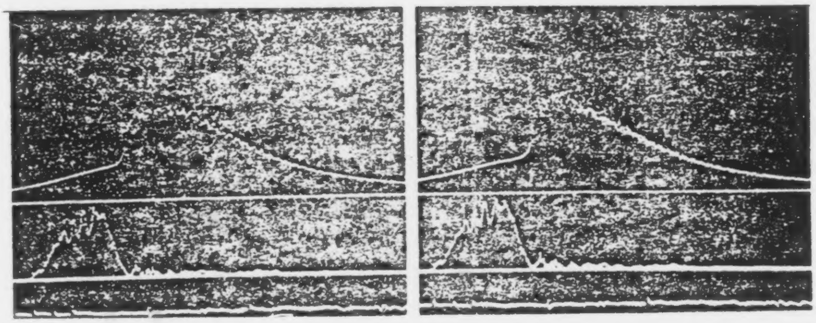
Very slight knocking was detected at Notches 2 and 4 at water concentrations in excess of 12 percent volume. Such knocking can be seen in the cylinder pressure photographs for Notch 4 presented in Figure 8.14.

The performance characteristics of the GE engine operating on water emulsions differs significantly from those of the EMD. The greatest improvements in BSFC occurred at the lower notches on the EMD engine whereas no benefits were derived at these positions on the GE. The performance of the two engines was nearly identical at



BASELINE DF-2

5% WATER/DF-2 EMULSION



12% WATER/DF-2 EMULSION

21% WATER/DF-2 EMULSION

FIGURE 8.14 EFFECT OF WATER EMULSIONS ON GE 12-7FDL CYLINDER PRESSURE CHARACTERISTICS, NOTCH 4

Notch 8. These gains amounted to about 0.5 percent reduction in BSFC accompanied by reductions in smoke and exhaust temperatures.

8.4 12-CYLINDER SUNFLOWER OIL TESTING

Upon successful completion of the two-cylinder engine sunflower oil (SFO) tests (Section 7.4), the SFO study was extended to include the 12-cylinder engines. A blend of 50 percent volume SFO/50 percent diesel fuel as well as 100 percent sunflower oil were tested in each engine. The SFO used in these tests was the same oil as that used in the two-cylinder engine; the fuel properties are presented in Table 7.4.

The objective of this task was to define the performance, fuel consumption, and combustion characteristics of the 12-cylinder GE and EMD engines while operating on blends of sunflower oil and DF-2. Blend tests were conducted at Notches 2, 4, 6, and 8. The fuel mass flow rates were held constant at the baseline values.

Sunflower Oil Test Results, EMD 12-645 E3

The EMD engine performance results were very similar to the results obtained during the two-cylinder engine testing. Brake horsepower decreased as the percentage of sunflower oil in the blends increased at all notch positions (see Figures 8.15 and 8.16). In part, the power reductions were caused by the reduced fuel heating value of the blends. The higher heating value of the sunflower oil was approximately 13 percent below that of DF-2. Shown on the performance plots is the heat consumption rate which is defined as the fuel consumption rate (lbs/hr) times the fuel higher heating value (BTU/lb), the product of which is BTU/hr. The heat rate ranged from about 1 to 1.2 percent lower than baseline DF-2 as a result of the reduced fuel heating value of the blends.

Thermal efficiency of the 50/50 blend was equal to or slightly greater than baseline DF-2 at Notches 4, 6, and 8, but fell 2.1 percent below baseline at Notch 2. Thermal efficiency of neat SFO was not as good, ranging from 3.3 percent to 0.6 percent below baseline at Notches 2 and 8, respectively.

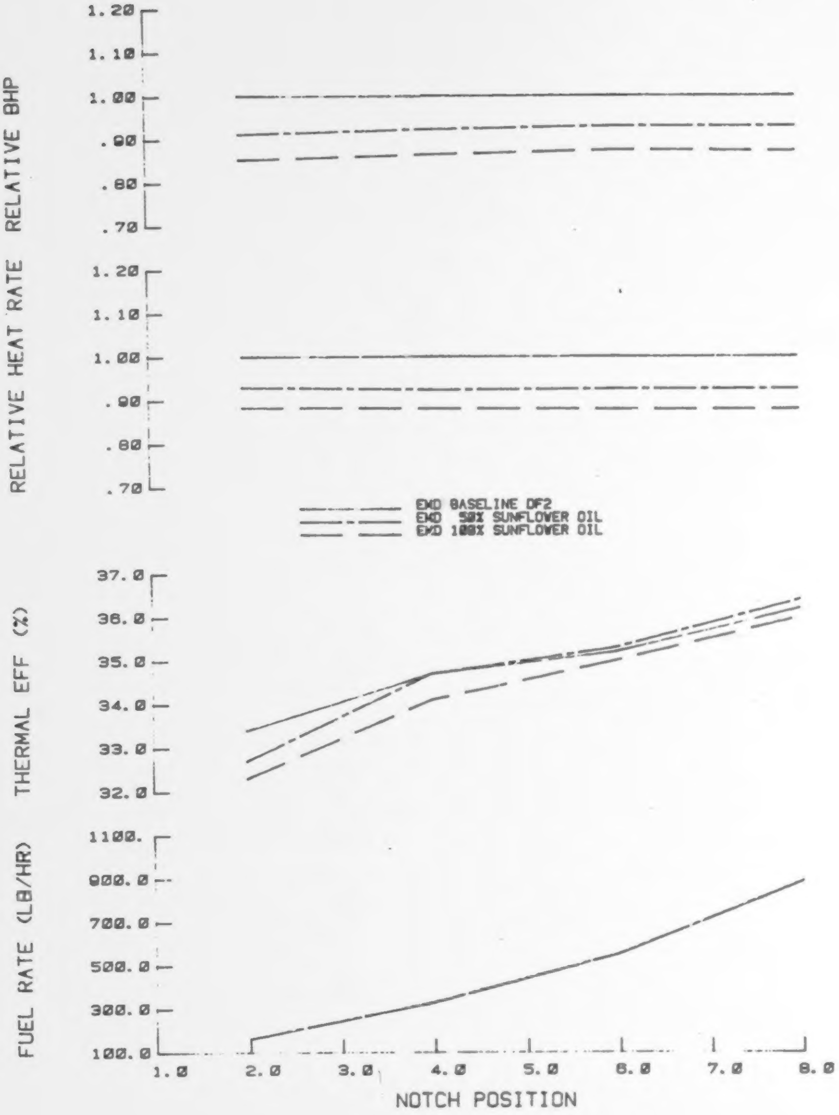


FIGURE 8.15 EFFECTS OF SUNFLOWER OIL/DF-1 BLENDS ON 12-CYLINDER EMD PERFORMANCE, ENGINE OPERATED AT BASELINE FUEL CONSUMPTION RATES

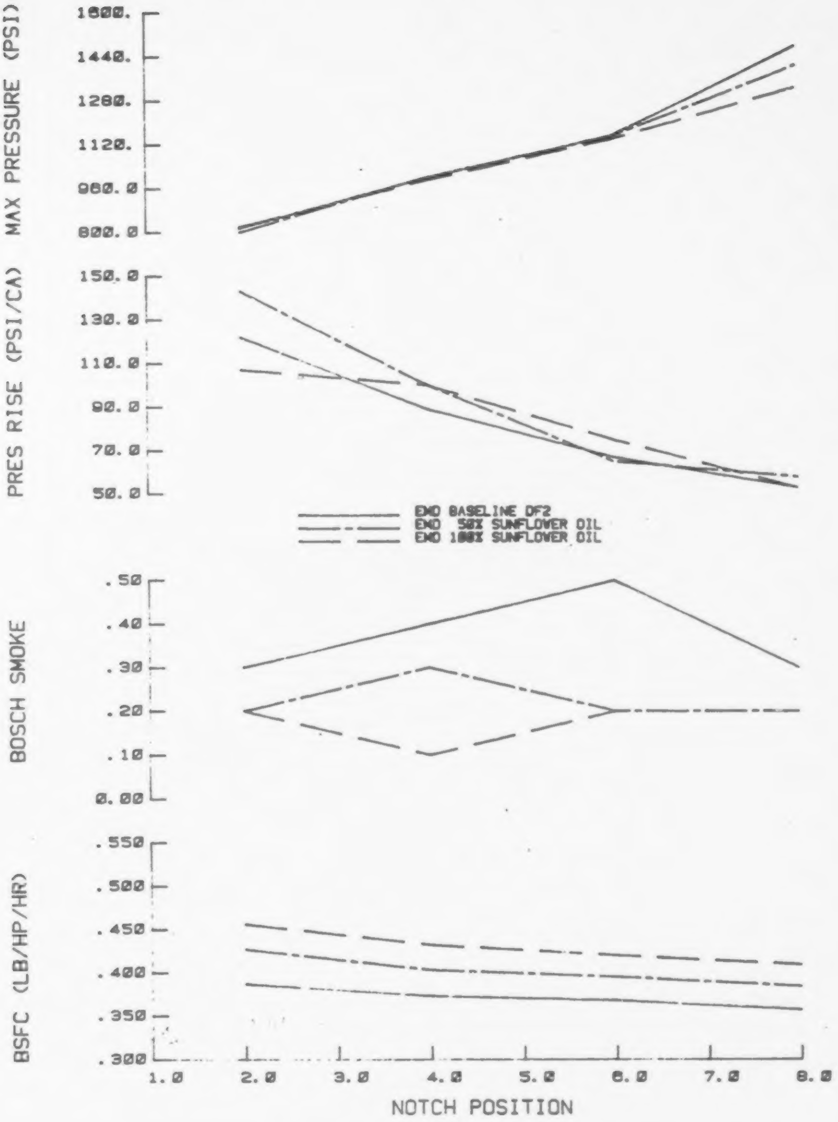


FIGURE 8.16 EFFECTS OF SUNFLOWER OIL/DF-2 BLENDS ON 12-CYLINDER EMD CYLINDER PRESSURE AND SMOKE CHARACTERISTICS, ENGINE OPERATED AT BASELINE FUEL CONSUMPTION RATES

A second sequence of tests was run at full baseline power at each notch position to determine the effect of neat SFO on thermal efficiency independent of power changes. An increase in fuel mass flow rate ranging from 26 lb/hr to 124 lb/hr at Notches 2 and 8, respectively, was needed to achieve baseline power outputs. Thermal efficiency of neat SFO was approximately equal to baseline at all notch positions. Thus, operating the engine at low power outputs can cause a reduction in thermal efficiency and also BSFC. Such power shifts, even on DF-2, should be avoided.

Sunflower Oil Test Results, GE 12-7FDL

Performance results of the General Electric SFO tests were similar to those of the EMD. The results of tests performed at fuel mass consumption rates equal to baseline showed thermal efficiencies slightly greater than baseline values at Notch 8 on both the 50/50 blend and neat SFO (Figure 8.17). Thermal efficiencies equaled baseline at Notch 6 and were about 10 percent below baseline at Notches 4 and 2. Bosch smoke increased considerably at these lower notches (Figure 8.18). Brake horsepower decreased by an amount equal to the reduction in fuel heat input at Notches 6 and 8, but decreased further at the lower notches due to the decline in thermal efficiency.

Thermal efficiency increased by a small amount at all notch positions when the engine was operated on the 50/50 blend and neat SFO at baseline power outputs, but the increases were not sufficient to bring the Notch 2 and Notch 4 thermal efficiencies up to baseline values. Thermal efficiency was 9.49 and 6.39 percent below baseline on neat SFO at Notches 2 and 4, respectively.

Both engines operated quite well on neat sunflower oil. Engine speed and power were stable and cylinder pressure characteristics were comparable to No. 2 diesel fuel. Smoke levels for the EMD engine were consistently at or below baseline levels; however, the smoke levels for the GE engine were greater than baseline levels at the lower notch positions. As with the two-cylinder engine testing, the engines were not operated on SFO for sufficient time to assess combustion chamber deposit effects, engine wear, reliability/durability or lubricating oil degradation.

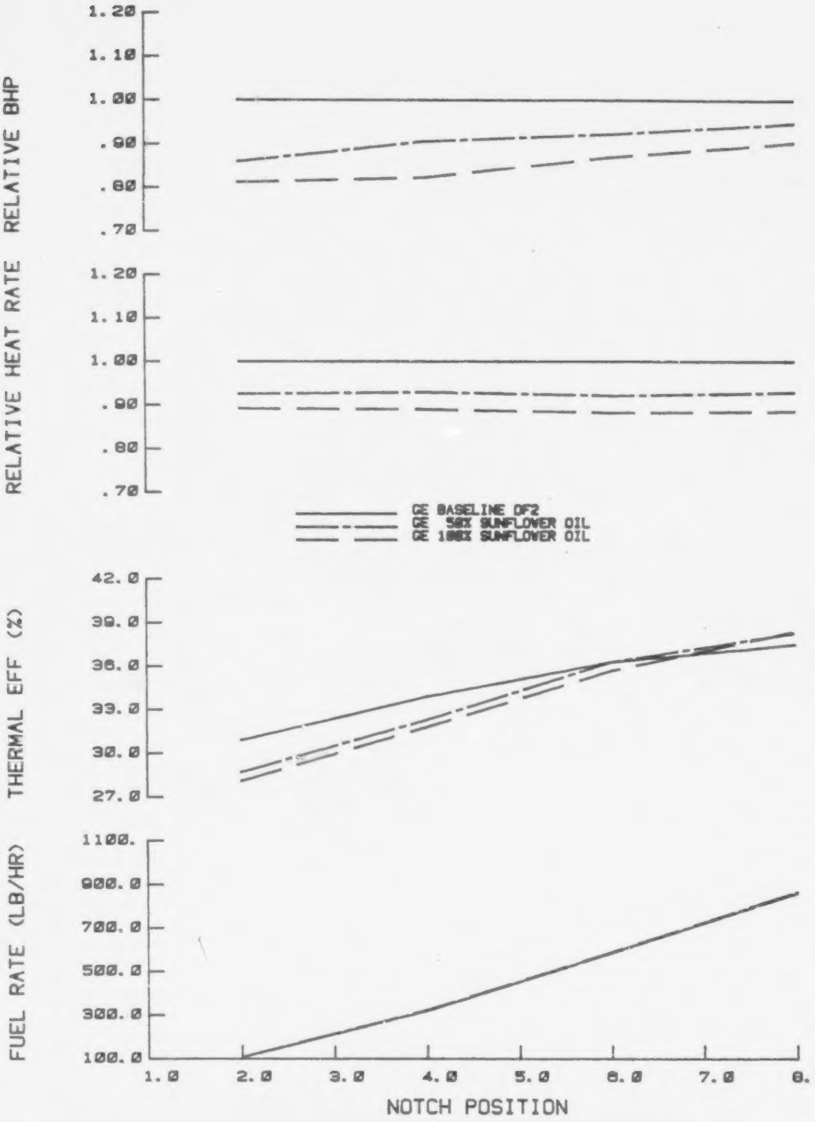


FIGURE 8.17 EFFECTS OF SUNFLOWER OIL/DF-2 BLENDS ON 12-CYLINDER GE ENGINE PERFORMANCE, ENGINE OPERATED AT BASELINE FUEL CONSUMPTION RATES

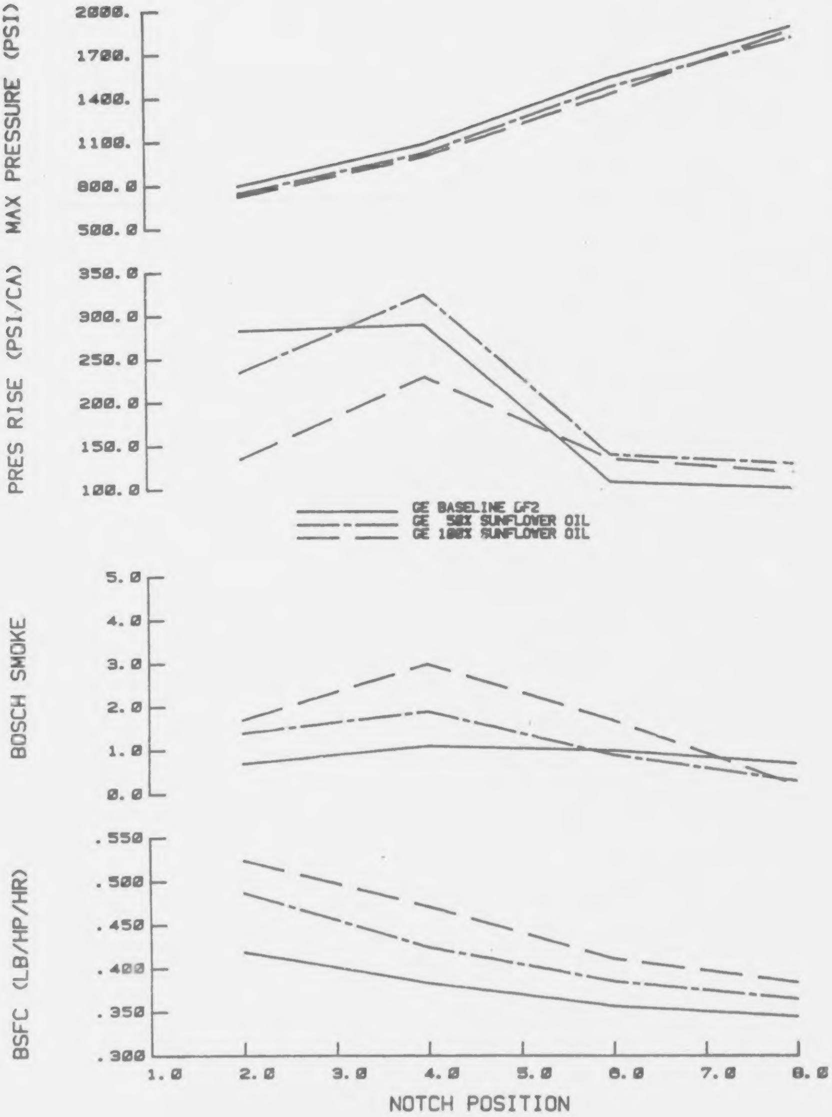


FIGURE 8.18 EFFECTS OF SUNFLOWER OIL/DF-2 BLENDS ON 12-CYLINDER GE CYLINDER PRESSURE AND SMOKE CHARACTERISTICS, ENGINE OPERATED AT BASELINE FUEL CONSUMPTION RATES

Certain precautions and recommendations should be considered if attempts are made to run sunflower oil as a DF-2 substitute. These precautions and recommendations are outlined in Section 7.4.

8.5 NO. 6 BLEND FUELS 12-CYLINDER ENGINE EXPERIMENTS

The fuel that ranks as the most promising candidate as an immediate low-cost substitute for DF-2 is the No. 6/No. 2 diesel blend. The availability and low cost of No. 6 fuel oils plus the potential for immediate use in medium-speed diesel engines with little or no modification are the reasons for the large amount of attention the blends have received recently.

The feasibility of using No. 6 blends was addressed in Section 6.1. This engineering study:

- Defined the range of No. 6 fuel oil properties currently available in the U.S.
- Defined the fuel property tolerance limits of common medium-speed diesel engines and used these limits as guidelines for blending fuels;
- Identified problems based on experience with trial blends in the chemical laboratory.

Laboratory engine tests on No. 6/DF-2 blends followed the guidelines for production of blends developed in the engineering study. The objectives of the 12-cylinder engine experiments were to:

- Determine the effects of a so-called limiting blend on locomotive fuel transfer and filtration systems.
- Determine the effects of a limiting blend on engine performance.
- Evaluate the effects of the blends on extended idling.

- Identify problem areas that may require further research before extensive field testing should be undertaken.

The approach taken to procuring a No. 6 stock and preparing a blend during the laboratory experiments simulated the procedure that a medium-speed diesel engine user might follow. A fuel oil supplier was contacted and a good quality No. 6 stock was selected based on the supplier's fuel property information. Since this information was limited to properties relevant to heating oil, the No. 6 was fully analyzed on receipt. The volume of No. 6 that could be blended with DF-2 to the limits of the guideline was estimated, and a small trial blend mixed. The trial blend was analyzed before preparing a large batch for engine testing.

Engine performance was evaluated at Notches 2, 4, 6, and 8 of both the EMD and GE engines. An extended idling test (48 hours continuous) was then completed on the EMD engine.

No. 6 Blends Analysis

The properties of the No. 6 fuel oil purchased for engine testing are presented in Table 8.2. The viscosity of the fuel (950 cSt at 40°C), while considerably greater than DF-2, was about average for a No. 6 available in the United States. The carbon residue and toluene insolubles were very high, and the compatibility ratings of 3 were poor. The insolubles and compatibility results suggested the presence of asphaltenes, which were likely to cause filtration and deposit problems.

The maximum No. 6 content of the blend was estimated using the proposed blend guideline (see Table 8.2). The high carbon residue content of the No. 6 stock limited the blend to a maximum of only 8.8 percent volume No. 6. The remaining blend properties fell within guideline values.

The compatibility test (ASTM D2781) was performed on the 8.8 percent volume blend. This was a non-standard test since the procedure calls for a 50/50 mix of No. 6 and No. 2D. The compatibility ratings were 1 on the 8.8 percent No. 6 blend as compared with 3 on the 50/50 blend. These results suggest that the compatibility test

Table 8.2 Properties of First No. 6 Fuel Oil

	No. 6 Fuel Oil	DF-2	Proposed Guidelines	No. 6/DF-2 Blend
Blend No. 6 Content, Vol. % (Wt %)	—	—	—	8.8 (10)
Gravity, °API	11.9	34.0	N.S.	32.0
Specific Gravity, 60°F	.9868	.8550	N.S.	.865
Density (lb/gal)	8.217	7.120	—	7.20
Flash Point, °F	296		150 min.	145°F
Pour Point, °F	54	—	—	-40°F
Viscosity				
cSt @ 40°C (104°F)	950	2.73	15.0 max.	3.65
cSt @ 122°F	365.9	—	—	—
Sulfur, Wt %	.67	.20	1.5 max.	.27
Carbon Residue Wt % on Oil	14.58	.35 est	1.5 max.	1.36 (A)
Ash, Wt %	.03	.01 est	.02	.012
Cetane Number	—	46.5	35 min.	42.4
Gross Heat of Combustion (BTU/lb)	19484	—	N.S.	19795
Pentane Insolubles, Wt %	6.85	—	—	.16
Toluene Insolubles, Wt %	2.72	—	—	.02
Compatibility, D2781				
Procedure A	3	—	—	1
Procedure B	3	—	—	1

NOTES:

A - Property that limited No. 6 content
est - Estimated

of the 50/50 blend may not be representative of the blends of other proportions. In this case, the compatibility of the 8.8 percent blend appeared to be better than the 50/50, but other blends of about 10 percent volume have shown the reverse.

A second batch of No. 6 fuel was obtained for comparison with the first. The carbon residue content was 7.89 percent (Table 8.3), considerably lower than the 14.8 percent of the first batch. A blend of 17.9 percent by volume No. 6 was possible before exceeding the 1.5 percent carbon residue limit of the guideline.

A 1000 gallon quantity of the 17.9 percent blend was mixed for engine testing. The No. 6 was heated prior to mixing, primarily to reduce its viscosity. The No. 6 and DF-2 were pumped into a mixing tee, then into a storage tank. Once mixing was completed, the blend was circulated in the tank for 24 hours to ensure homogeniety. Analysis of a sample from the 1000 gallon batch revealed a carbon residue of 2.03 percent (see Table 8.3), higher than the guideline limit of 1.5 percent, possibly due to an error in mixing.

A test was performed to determine if blend filtration on the engine was indeed a problem as the chemical laboratory analyses had indicated. A 450 gallon batch of blend was prepared at 8.8 percent volume of the high carbon residue No. 6 (first batch). The filter test was performed on the GE fuel filtration system. The mean pore size of the GE filter was 5 microns. The blend was pumped through the fuel filter at the Notch 8 mass fuel rate of 860 lbs/hr. Fuel pressures were monitored before and after the filter to indicate plugging. The fuel was then pumped to a 500 gallon storage tank.

The 450 gallons passed through the General Electric filter with no indications of filter plugging. The fuel filter was removed and inspected for deposits. There appeared to be a slight collection of asphaltene on a few pleats of the fuel filter. A rough calculation indicated that the amount of fuel that passed through the GE fuel filter element was twice that which plugged the small chemical laboratory filters per square inch. It was concluded that the chemical laboratory filtration tests were not representative of filter plugging on locomotive engines. A more representative filtration test should be devised. This test could substitute filter paper from a locomotive filter for laboratory filter elements.

Table 8.3 Properties of Second No. 6 Fuel Oil

	No. 6 Fuel Oil	DF-2	Proposed Guidelines	No. 6/DF-2 Blend
Blend No. 6 Content, Vol. % (Wt %)	---	---	---	17.9 (19)
Gravity, °API	21.9	34.0	N.S.	31.6
Specific Gravity, 60°F	.9224	.8550	N.S.	.8676
Density (lb/gal)	7.682	7.120	---	7.23
Flash Point, °F	171		150 min.	140°F
Pour Point, °F	-28	---	---	3°F
Viscosity				
cSt @ 40°C (104°F)	108.4	2.73	15.0 max.	4.46
Sulfur, Wt %	.85	.20	1.5 max.	.32
Carbon Residue Wt % on Oil	7.89	.35 est	1.5 max.	2.03 (A)
Ash, Wt %	.02	.01 est	.02	.01
Cetane Number	---	46.5	35 min.	44.9
Gross Heat of Combustion (BTU/lb)	---	19484	N.S.	19795
Pentane Insolubles, Wt %	3.69	---	---	.63
Toluene Insolubles, Wt %	0.46	---	---	.07
Compatibility, D2781				
Procedure A	1	---	---	1
Procedure B	1	---	---	1

NOTES:

A - Property that limited No. 6 content
est - Estimated

No. 6 Blends, 12-Cylinder Engine Test Results

The 12-cylinder engines were operated in their standard configurations throughout the blends tests. The fuel mass flow rates were held equal to that of baseline DF-2.

The results of the No. 6 blends performance test are presented in Figure 8.19 through 8.22. Shown on the performance plots is energy consumption rate (heat rate), which is defined as the fuel consumption rate (lb/hr) times the fuel higher heating value (BTU/lb), the product of which is BTU/hr. The heat rate ranged from 1 to 4 percent greater than the baseline diesel fuel as a result of the increased fuel heating value of the blends, yet brake horsepower was equal to or less than baseline values. The actual heat rate and horsepower values are presented in Table 8.4. The largest power reductions amounted to approximately 3 percent.

The low power levels were due to a reduction in thermal efficiency, which fell below baseline values at all notch positions on both engines (see Table 8.4). Power output fell below baseline when the reduction in thermal efficiency was greater than the increase in fuel energy consumption rate. Thermal efficiencies of the 8.8 and 17.9 percent volume blends of each engine were nearly identical.

Cylinder pressure characteristics were not appreciably changed by the heavy fuels blends. Bosch smoke levels were likewise unchanged with the exception of a single Notch 4 data point on the 8.8 percent blend when testing the GE. This point is suspected of being in error.

A single problem marred the No. 6 blends test. Fuel filter elements mounted on the Flo-tron plugged after a short period during the first No. 6 test. These filters were of the small spin-on type used on diesel trucks. The problem was eliminated by placing the Flo-tron downstream of the primary engine filters, still using the spin-on filters.

The blends were not heated upstream of the primary filters. The lowest fuel temperature encountered was 69°F. While problems did not occur with this particular

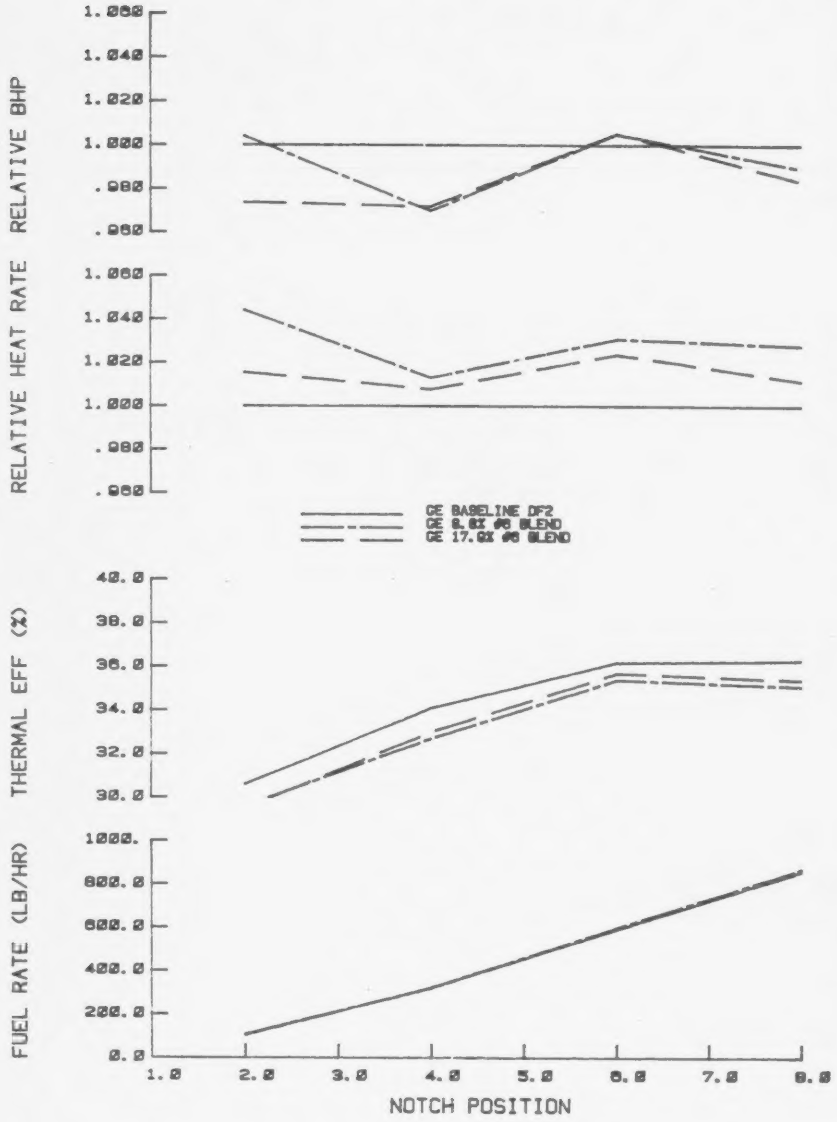


FIGURE 8.19 GE 12-7FDL ENGINE PERFORMANCE USING NO. 6/DF-2 BLENDS

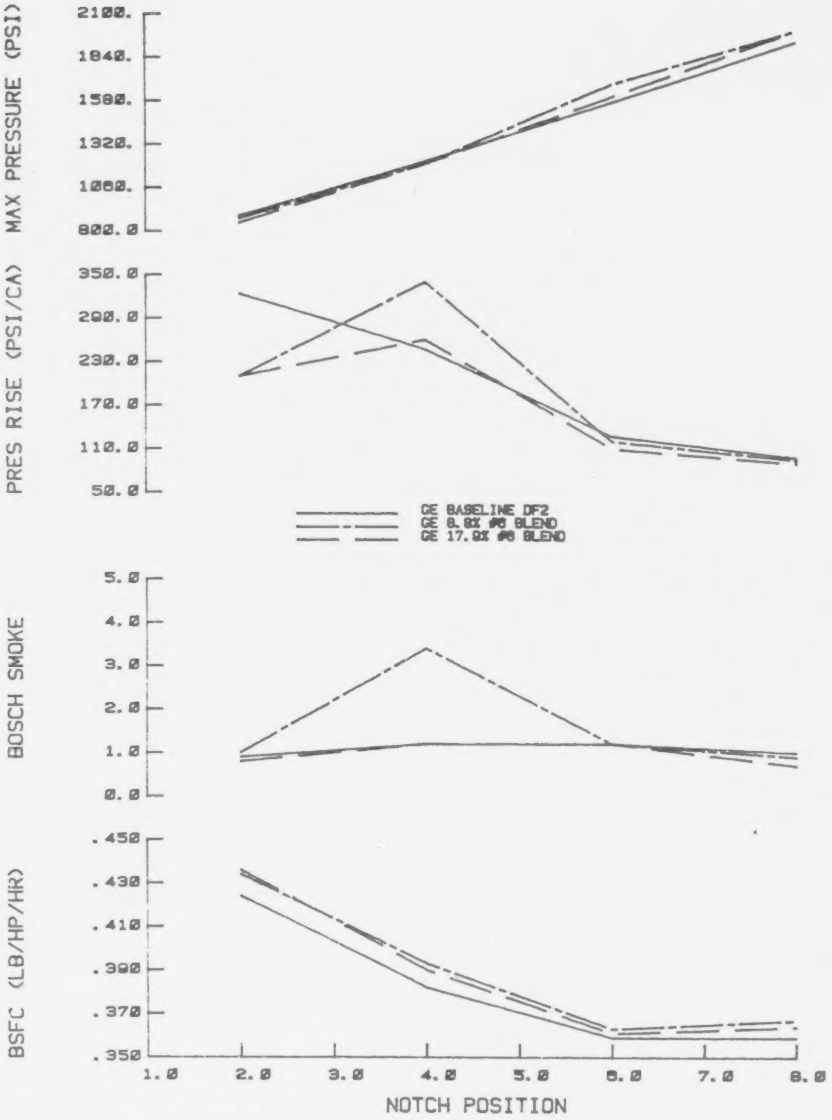


FIGURE 8.20 GE 12-7FDL ENGINE SMOKE AND CYLINDER PRESSURE CHARACTERISTICS, NO. 6/DF-2 BLENDS

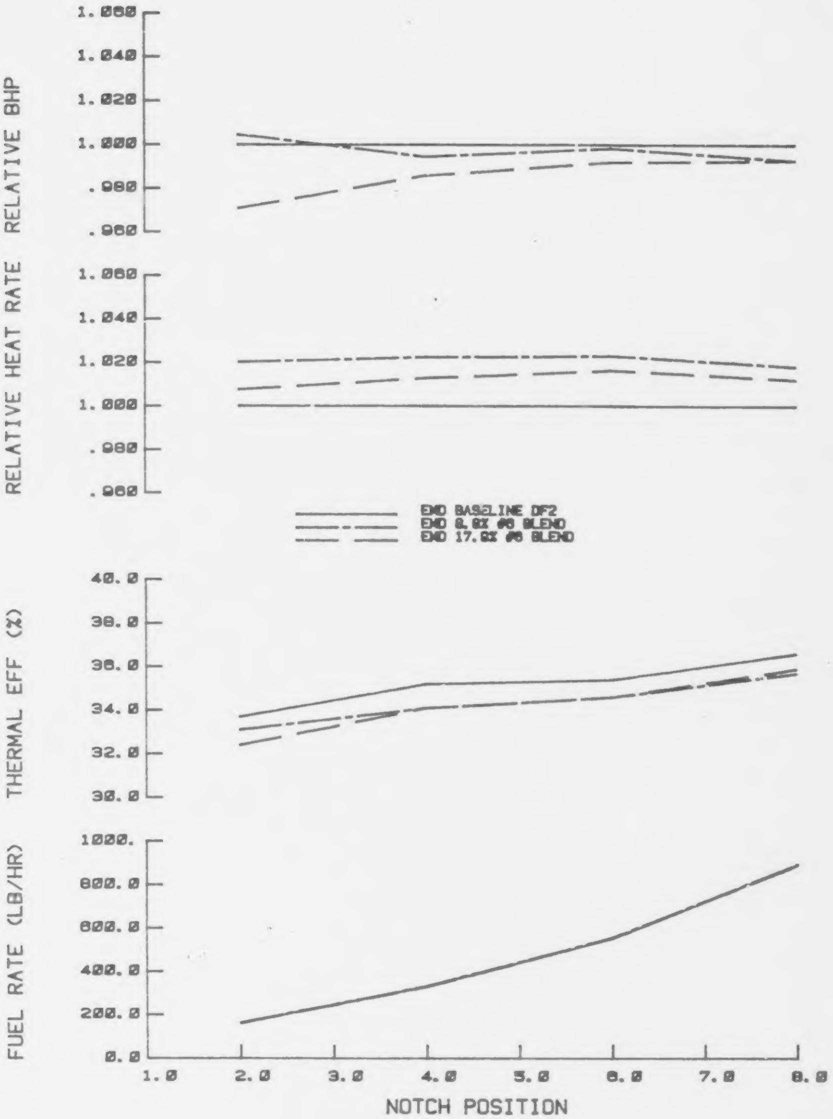


FIGURE 8.21 EMD 12-645 E3 ENGINE PERFORMANCE USING NO. 6/DF-2 BLENDS

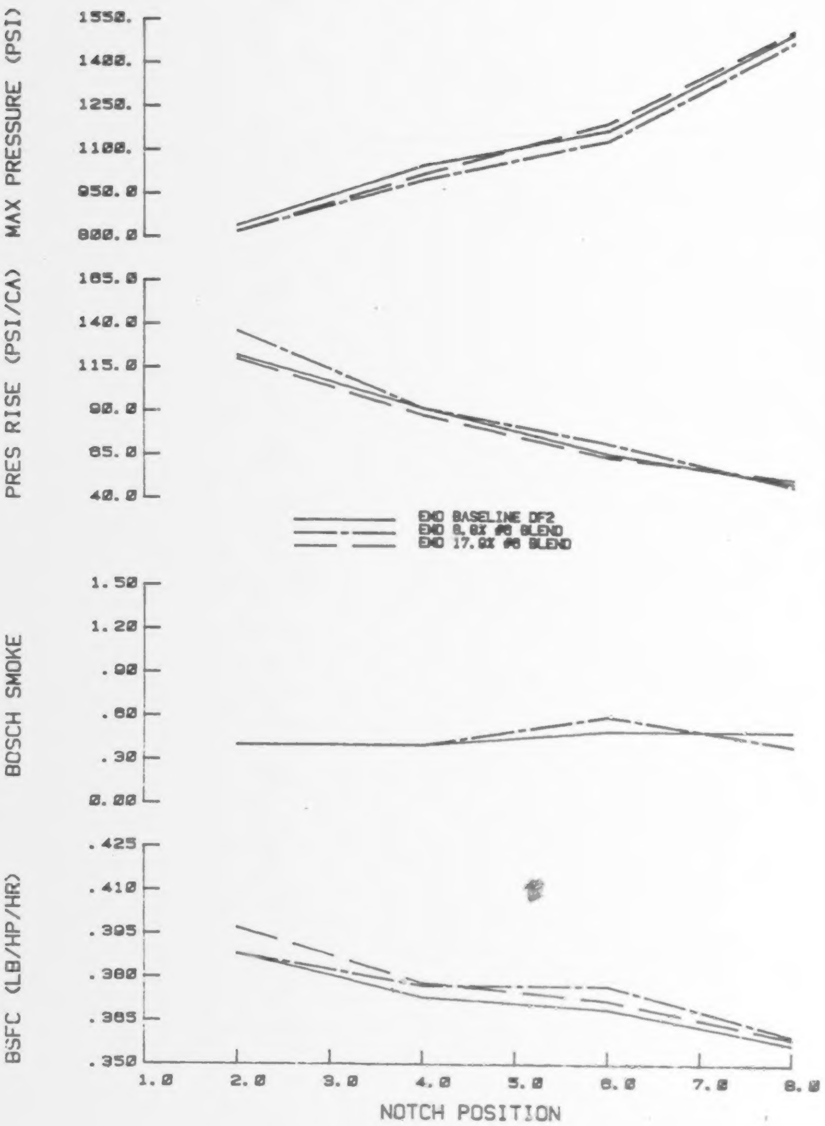


FIGURE 8.22 EMD 12-645 E3 SMOKE AND CYLINDER PRESSURE CHARACTERISTICS, NO. 6/DF-2 BLENDS

blend at this temperature, railroad fuel tests indicate that difficulties may be encountered at lower fuel temperatures.

Table 8.4 Efficiency and Horsepower Reductions Observed During No. 6/DF-2 Blends Tests on the 12-Cylinder Engines

Engine	No. 6 Blend	Notch	Increase in Fuel Energy Consumption (%)	Decrease in Brake Thermal Efficiency (%)	Increase in Brake Horsepower (%)
GE	8.8% No. 6 (First)	2	4.4	3.3	0.4
		4	1.3	4.2	-3.0
		6	3.1	2.2	0.5
		8	2.8	3.4	-1.1
GE	17.9% No. 6 (Second)	2	1.5	3.7	-2.6
		4	0.8	3.3	-2.8
		6	2.4	1.4	0.5
		8	1.2	2.5	-1.7
EMD	8.8% No. 6 (First)	2	2.0	1.8	0.5
		4	2.2	3.2	-0.6
		6	2.3	2.3	-0.2
		8	1.8	2.5	-0.7
EMD	8.8% No. 6 (Second)	2	0.8	3.9	-2.9
		4	1.3	3.2	-1.4
		6	1.6	2.3	-0.8
		8	1.2	1.9	-0.7

The results of the No. 6 blend tests indicate that reductions in thermal efficiency are likely with standard configuration EMD and GE engines. These reductions may be equal to or greater than the increased fuel heating value of the No. 6 blends, resulting in either an even trade-off or a net reduction in brake horsepower output. The benefits from the increased fuel heating content should not be relied upon as an added benefit (besides cost reductions) in No. 6 blend use; thermal efficiency reductions may more than offset the increased heat content and consume some of the per gallon cost savings of the blends.

These results contradict those obtained by a U.S. medium-speed diesel manufacturer and a railroad that is conducting field tests of heavy blended fuels. In both cases, efficiencies were high and a cost savings could be realized from the increased energy content of the blends. While these results are more optimistic, the reader is cautioned against relying on increased blend energy content for cost benefits until further test data is available.

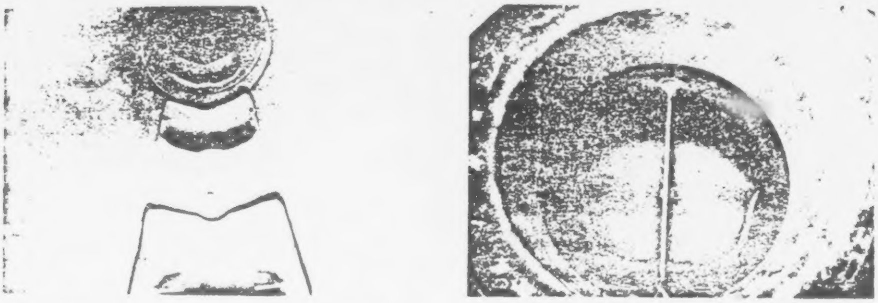
The long-term adverse effects of residual fuel oils on slow-speed marine diesel engines are well documented. These include combustion chamber and exhaust system carbon build-up, exhaust valve erosion due to vanadium attack, ring and liner wear resulting from sulfur attack, abrasive wear from cracking catalyst fines and fuel filter plugging. These problems are also likely to plague medium-speed diesel engines operating on residual fuel/DF-2 blends. Long-term laboratory and field tests are recommended to accurately define the fuel property tolerance limits of current medium-speed diesels and define and solve fuel handling, engine wear, durability and deposits problems before heavy blended fuels are accepted for field use.

No. 6 Blends Idling Test

An idle test was performed on the 12-cylinder EMD engine using the 17.9 percent volume No. 6 fuel oil blend. The engine was run continuously for 48 hours at standard idle (315 rpm). Precautions were taken to prevent accidental turbocharger destruction such as several railroads had experienced. The accidents on the EMDs occurred when the turbo screen, which is bolted between the turbocharger and exhaust manifold, clogged with carbon and unburned fuel deposits, causing the engine to surge and ignite an exhaust fire. The turbochargers then oversped to destruction. The fuel consumption rate, exhaust backpressure and airbox pressure increased as the screen clogged. A sensor was attached to the injector rack linkage to give the engine operator an indicator of rack position while inside the control room. The fuel flow rate measurement also provided an indicator of changes in engine fuel consumption rate. Pressures and temperatures were recorded before and after the turbocharger screen as indicators of screen plugging. The turbocharger screen was removed, inspected and photographed before and after testing. The exhaust manifold and turbocharger were likewise photographed (Figure 8.23).

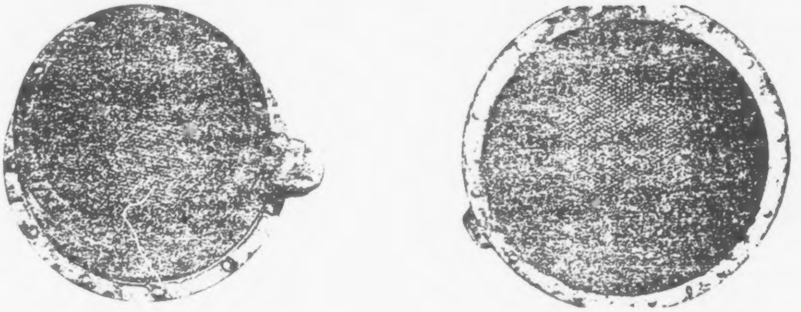
The 48-hour idle test was completed without problem. Ambient temperature ranged from 44 to 72°F. The pressures, temperatures, and rack position did not change appreciably. Inspection of the turbocharger screen revealed that it was coated with a heavy tar-like material but none of the holes were badly obstructed (Figure 8.24). The trap in the bottom of the turbo screen housing was filled with liquid fuel. The entire system was reassembled after photographing and the engine operated at Notch 8 on DF-2 to remove the deposits.

The results indicate that the EMD engine can idle for 48 hours on the 17.9 percent blend in mild climates; however, this should not be taken as an indicator that the engine could idle successfully for longer periods or in colder environments. The ambient temperatures and duration limits are not known. The experiences of the Canadian National, Union Pacific, and the Seaboard Systems Railroads are fairly good indicators that idling on heavy fuel blends is likely to cause exhaust system deposits. Their experiences identified the extent to which deposits are likely to occur and determined the mechanism by which turbochargers were destroyed. Further work is needed to devise methods to prevent significant buildup of either raw fuel or deposits in exhaust systems.



Exhaust Manifold Viewed from Turbocharger End

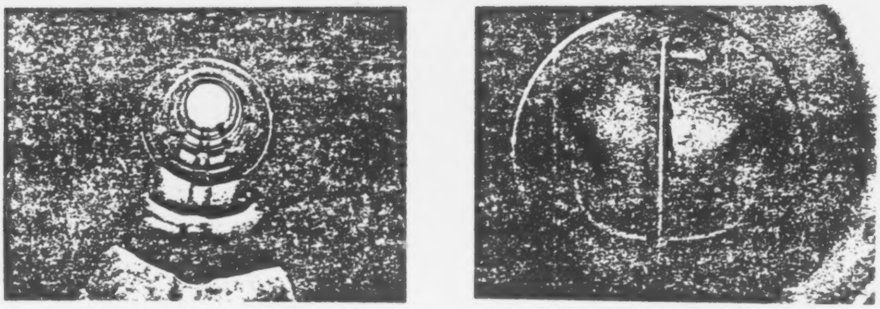
Turbocharger Exhaust Inlet



Turbocharger Screen, Exhaust Inlet Side

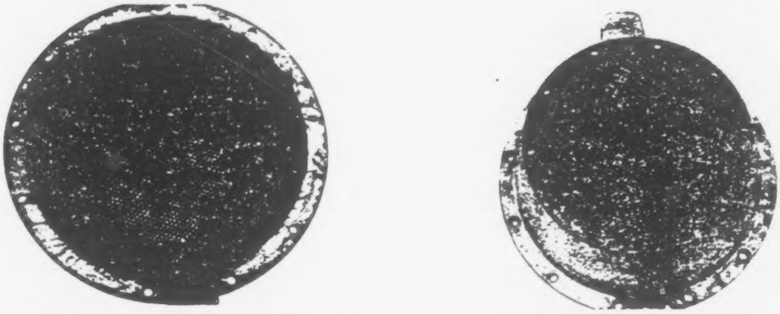
Turbocharger Screen, Exhaust Outlet Side

FIGURE 8.23 CONDITION OF THE 12-CYLINDER EMD EXHAUST SYSTEM PRIOR TO 48-HOUR IDLE TEST USING NO. 6/DF-2 BLEND



Exhaust Manifold Viewed from Turbocharger End

Turbocharger Exhaust Inlet



Turbocharger Screen, Exhaust Inlet Side

Turbocharger Screen, Exhaust Outlet Side

FIGURE 8.24 DEPOSITS FORMED IN THE EXHAUST SYSTEM OF THE 12-CYLINDER EMD IN 48 HOURS OF IDLING USING A NO. 6/DF-2 BLEND

REFERENCES

1. Foster, R. W., "Alternative Fuels for Medium-Speed Diesel Engines - Project Management Master Plan", E:F Technology, Inc., April 1979.

2. Baker, Q. A., et. al., "Alternative Fuels for Medium-Speed Diesel Engines Project, First Research Phase Final Report, Off-Specification Diesel Fuels, Simulated Coal-Derived Fuel and Methanol," SwRI Report No. 11-5361, FRA Report No. FRA/ORD-80/40.I (DOE/FRA joint report), January 1981.

3. Baker, Q. A., et. al., "Alternative Fuels for Medium-Speed Diesel Engines Second Research Phase Final Report, Synthetic Fuels, Alcohol Emulsions, Off-Specification Diesel Fuels and Methanol," SwRI Report No. 05-5361-002, FRA No. FRA/ORD-80/40.II, September 1981.

4. Storment, J. O. and K. S. Springer, "Assessment of Control Techniques for Reducing Emissions from Locomotive Engines," SwRI Report No. AR-884, April 1973.

5. Telephone conversation with Mr. J. G. Hoffman, General Electric, March 3, 1981.

6. Telephone conversation with Mr. T. N. Pratt, Electro-Motive Division of General Motors, December 11, 1980.

7. N. R. Sefer, Q. A. Baker, "Characterization of Residual Fuels and Their Blends with Railroad Diesel Fuel," ASME Paper No. 83-DGP-6, February 1983.

8. E. M. Shelton, "Heating Oils, 1981," Report No. DOE/BETC/PPS-81/4, August 1981.

REFERENCES, Cont'd.

9. Foster, R. W., "Integrated Test Planning Guidelines for Evaluation of Alternative Fuel and Energy Conservation Systems using the SwRI Medium-Speed Diesel Engine Laboratory and Full-Scale Rail or Marine Motive Power Equipment," E.F. Technology, Inc., February 1983.

10. "Alternative Fuels Field Testing Guidebook", Association of American Railroads, Working Draft, November 17, 1982.

11. "Test Techniques for Conducting Full-Scale Railroad Diesel Locomotive Tests," Coordinating Research Council, January 1959.

12. "New Developments by B.I.C.E.R.A.," The Oil Engine and Gas Turbine, November 1953.

13. Obert, E. F., Internal Combustion Engines and Air Pollution, Third Edition, Intext Educational Publishers, 1973.

14. Gupta, C. P., et. al., "Effects of Multiple Introduction of Fuel on Preflame Reactions in a Compression Ignition Engine," SAE Paper No. 650608, May 1965.

15. Baker, Q. A., "Expanding Diesel Engine Cetane Number Limits Through Staged Injection," SAE Paper No. 830246, February 1983.

16. "Operation of EMD 567C Engine on Methanol Fuel," SwRI Report No. AR-1180, July 15, 1977.

17. Owens, E. C., "Effects of Alcohol Fuels on Engine Wear," SAE Paper No. 800957, June 1980.

References, cont'd.

18. Ryan, T. W., et. al., "The Use of Hybrid Fuel in a Single-Cylinder Diesel Engine," SAE Paper No. 801380, February 1980.

19. Ryan, T. W., et. al., "Alternative (Hybrid) Fuels for Highway Transportation," DOE Final Report No. DEAC 04-79C54245, March 1982.

20. Coon, C. W., "Multi-Cylinder Diesel Engine Tests with Unstabilized Water-in-Fuel Emulsions," USCG Report No. CG-D-27-80, March 1981.

21. Wisniowski, H. V., Jackson, D. R.; "Further Results Obtained with Spectrographic Sampling Method of Assessing the Wear of Cylinders and Piston Rings," National Research Council of Canada - Mechanical Engineering Report ME-219, January 1966.

22. Telephone conversation with Mr. D. R. Jackson, Canadian National Railroad, September 30, 1982.

APPENDIX A

BASELINE DIESEL FUEL

STAGED INJECTION PERFORMANCE PLOTS

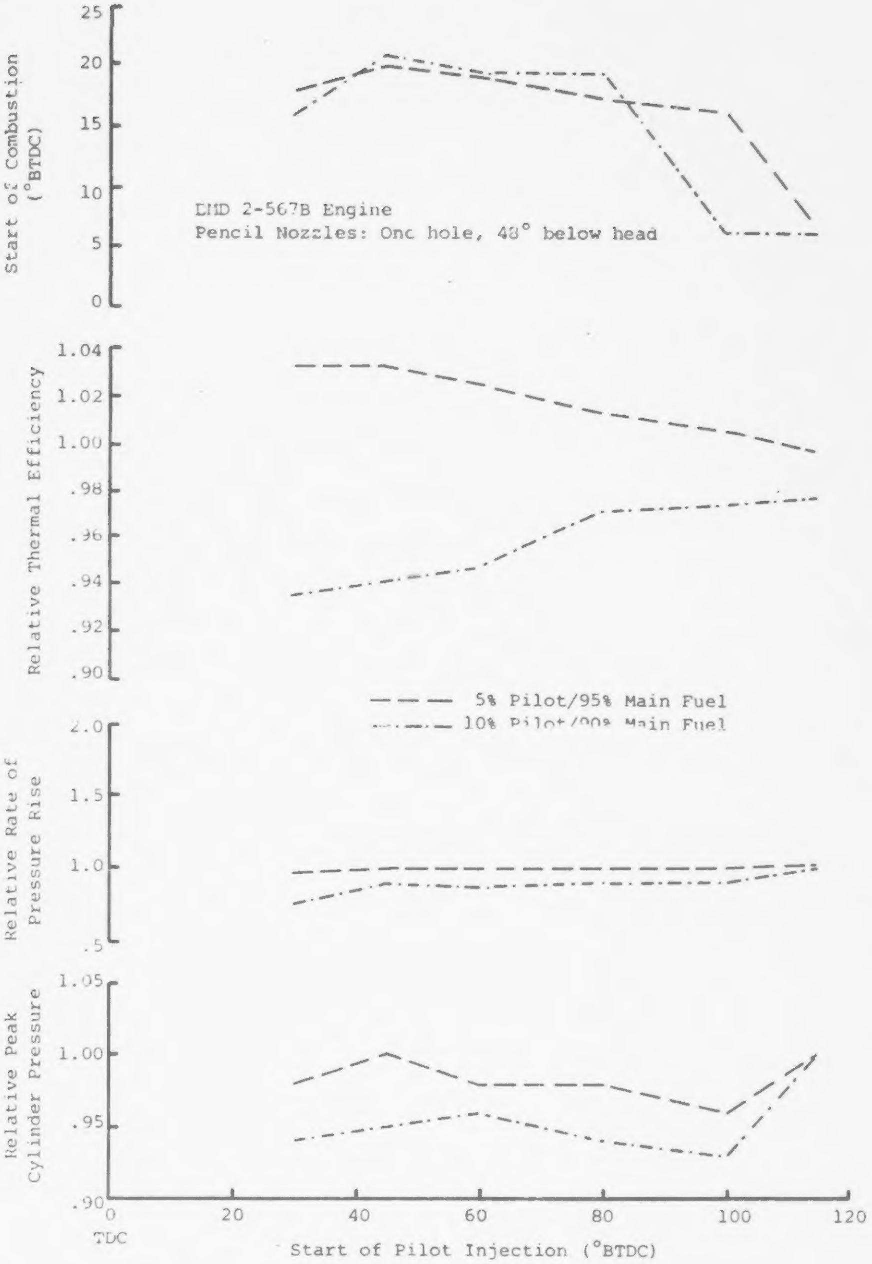


FIGURE A-1 NOTCH 4, BASELINE DF-2 STAGED INJECTION PERFORMANCE RESULTS

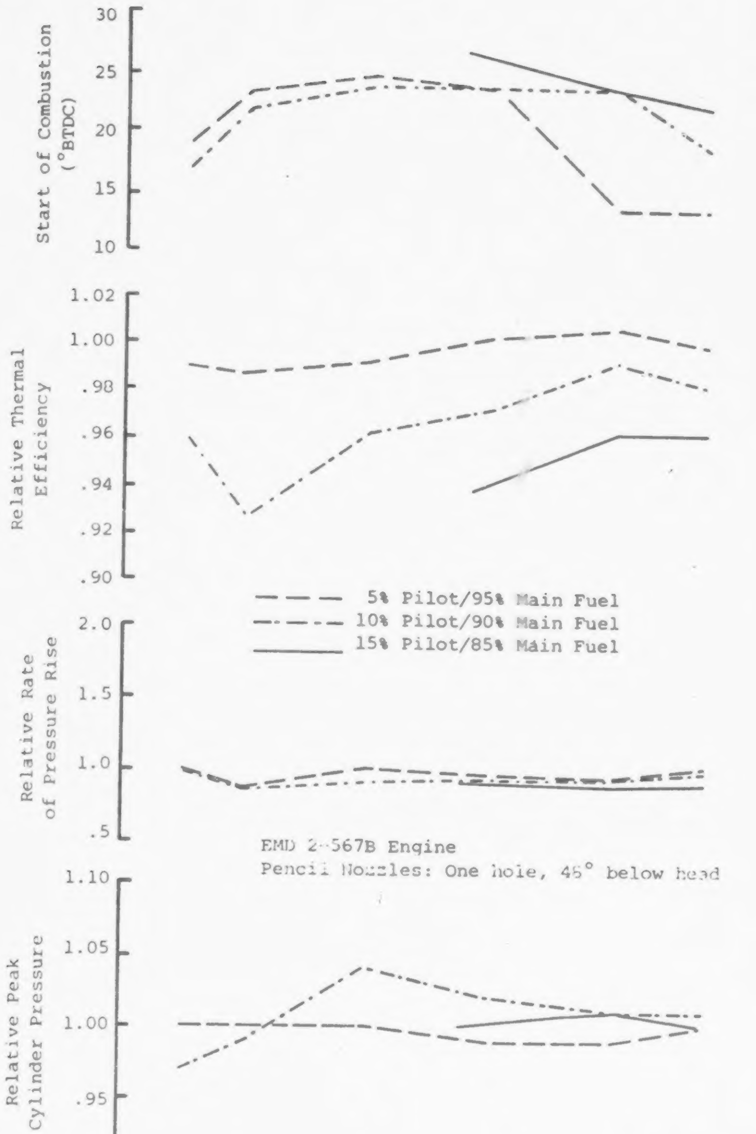


FIGURE A-2 NOTCH 8, BASELINE DF-2 STAGED INJECTION PERFORMANCE RESULTS

APPENDIX B

30.8 AND 24.0 CETANE FUEL BLENDS STAGED INJECTION PERFORMANCE PLOTS

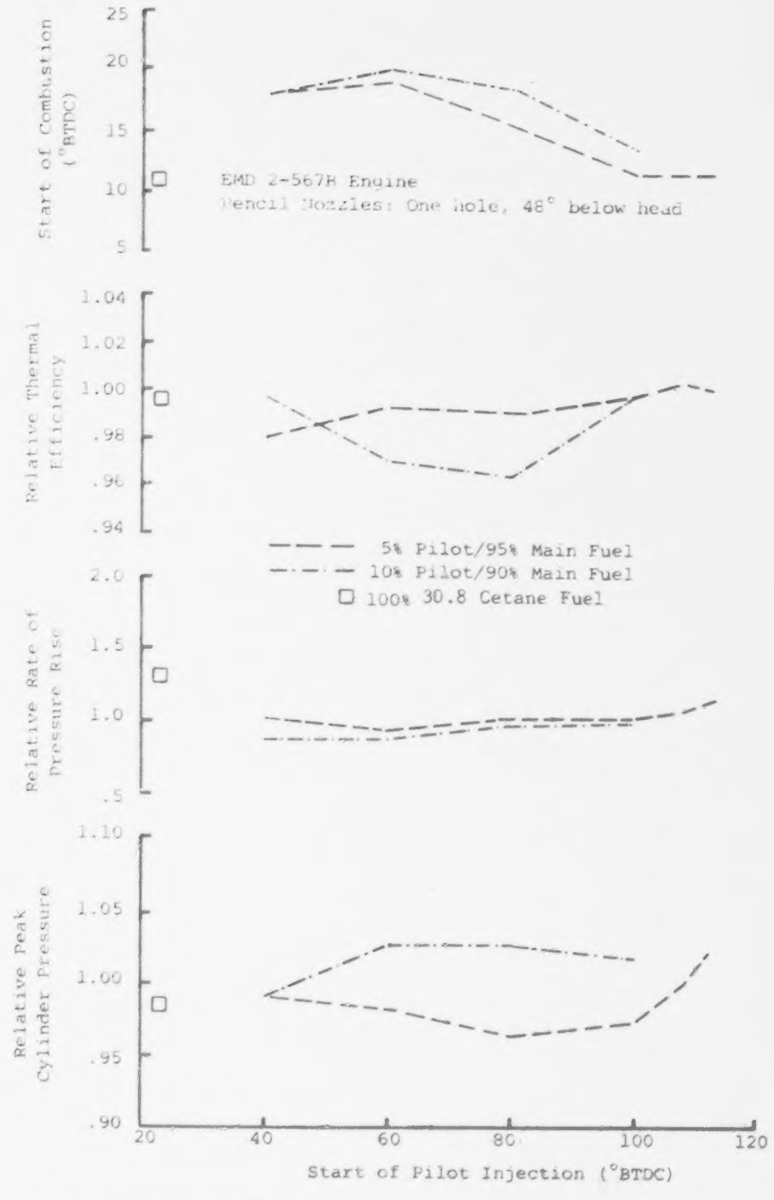


FIGURE B-1 NOTCH 4, 30.8 CETANE FUEL STAGED INJECTION PERFORMANCE RESULTS

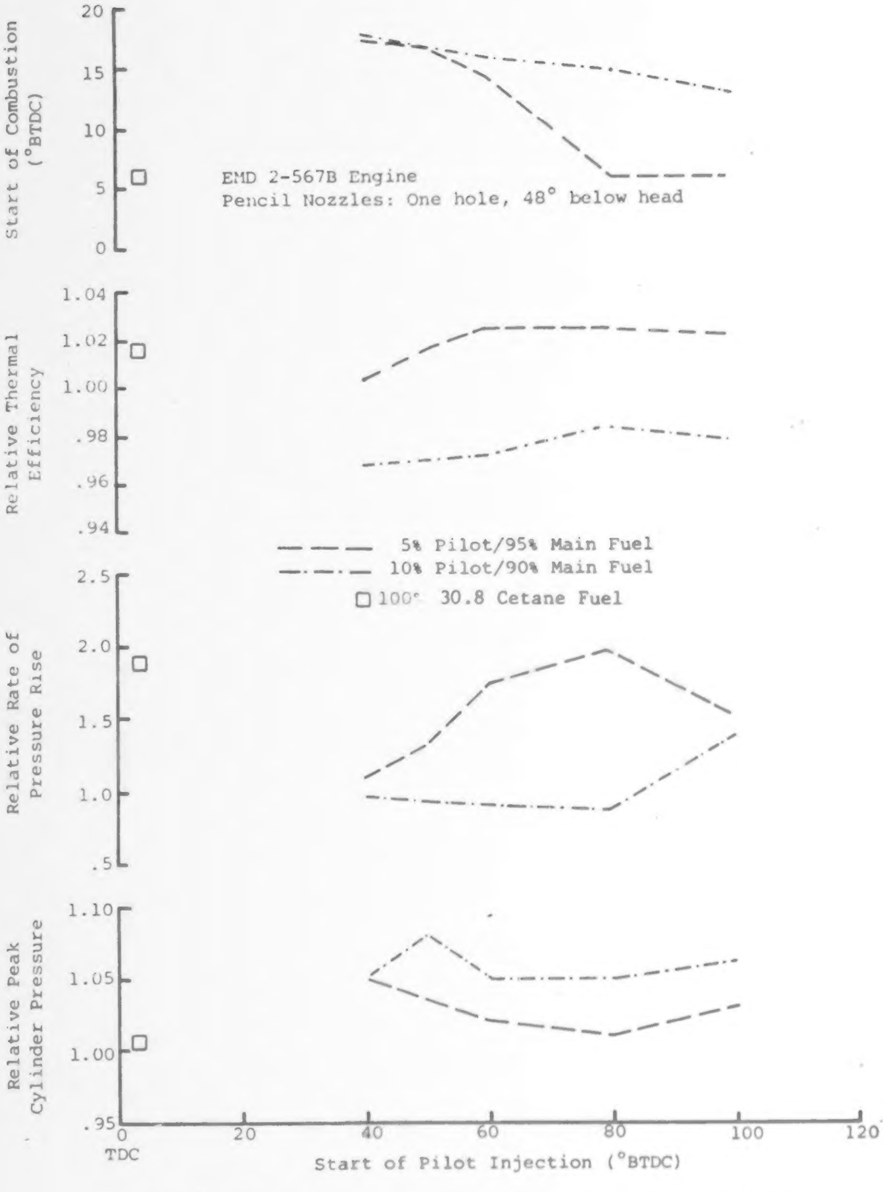


FIGURE B-2 NOTCH 8, 30.8 CETANE FUEL STAGED INJECTION PERFORMANCE RESULTS

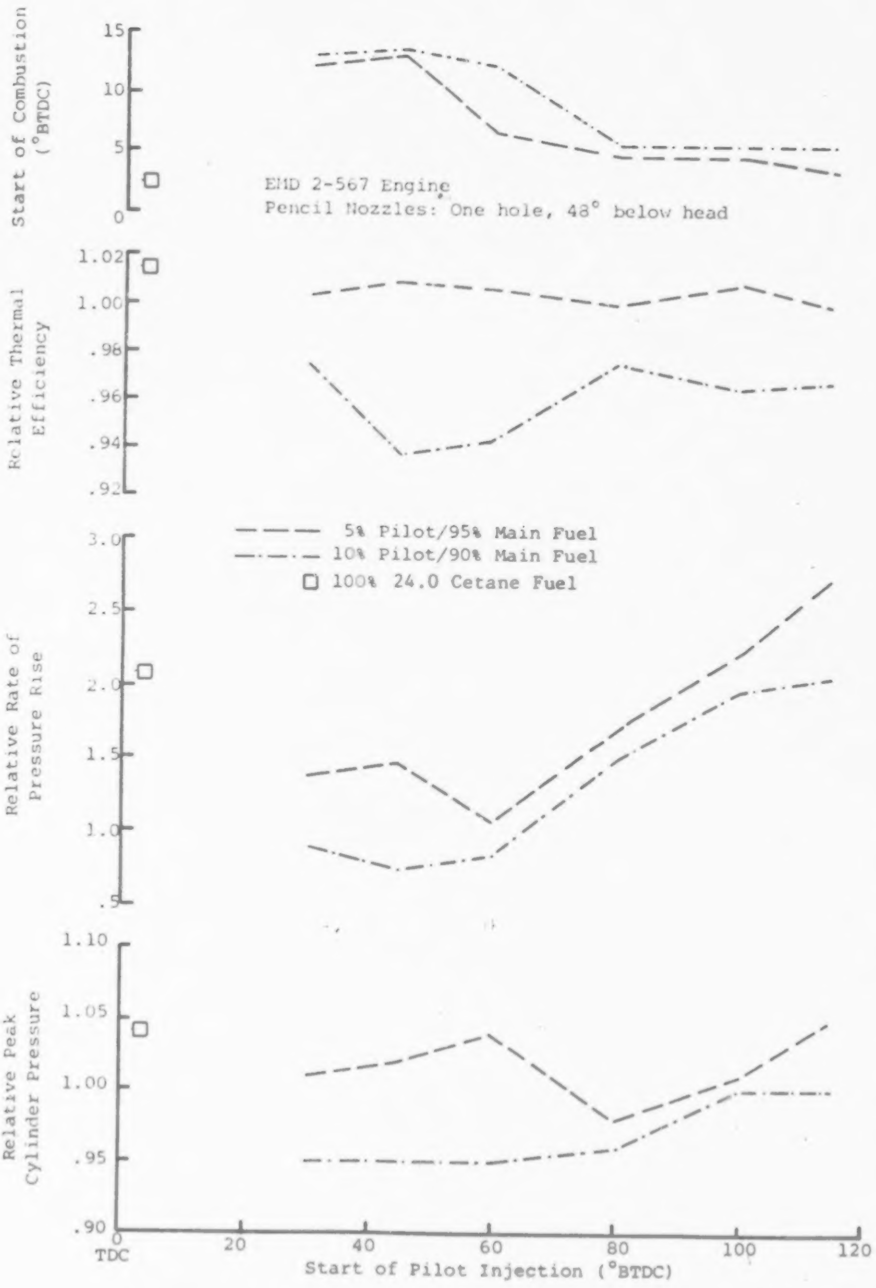


FIGURE B-3 NOTCH 4, 24.0 CETANE FUEL STAGED INJECTION PERFORMANCE RESULTS

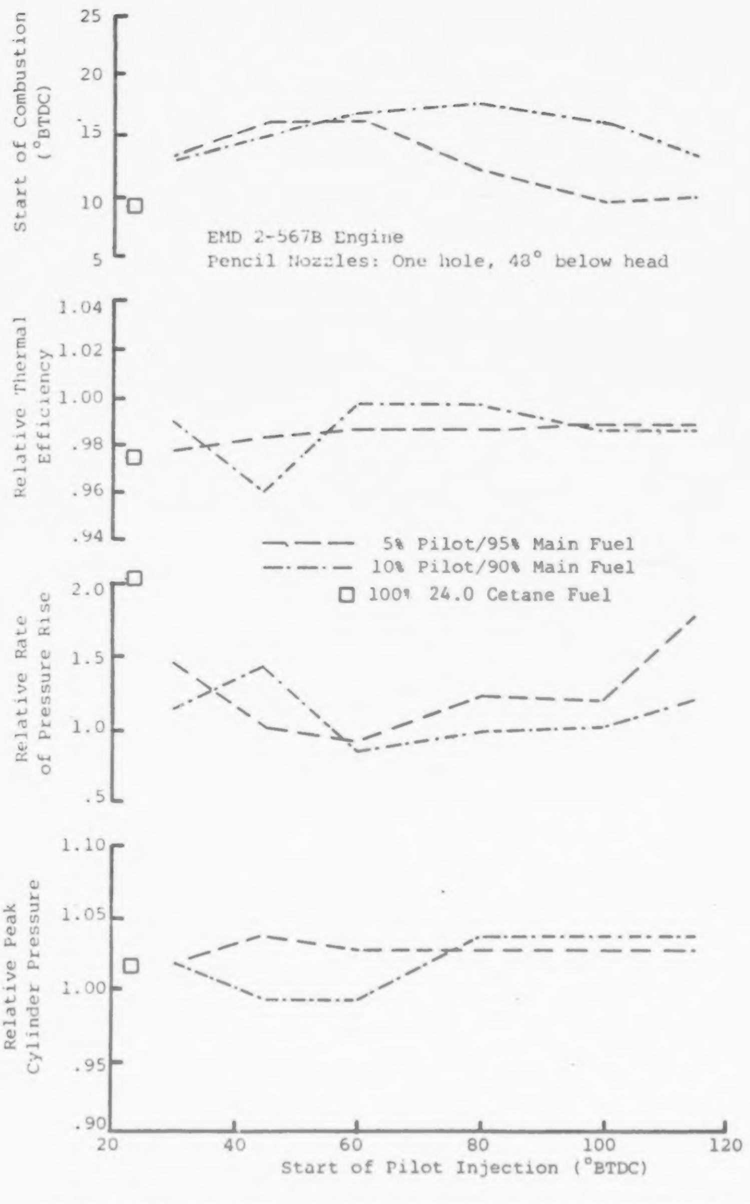


FIGURE B-4 NOTCH 8, 24.0 CETANE FUEL STAGED INJECTION PERFORMANCE RESULTS

APPENDIX C

SPECTROGRAPHIC ANALYSIS TECHNIQUES

SPARK SOURCE EMISSION SPECTROSCOPY

Spark source emission spectroscopy involves placing a sample into a 300 volt spark between a rotating graphite wheel and a graphite electrode. The spark serves as a detector source. Specific photon emissions from the sample burned in the spark pass through a monochromator, and then fall on a detector. Metals with atomic numbers of 4 (boron) or more are detected simultaneously using this method.

Advantages to the method include a minimum sample preparation, inexpensive operation, and simultaneous metal detection. Disadvantages include large original expense to set up an instrument and a rather low accuracy of 20 percent. Another problem is the possible lack of complete burning of a wear particle in the spark. If a partially burned particle is returned to the sample, it may not be sampled again and false low results may occur. Such elements as sulfur, phosphorus, chlorine, and bromine are not detected.

ATOMIC ABSORPTION

Atomic absorption involves aspiration of a sample into a high temperature air acetylene or acetylene-nitrous oxide flame. A source lamp specific for a single element sends a beam through the flame where the specific element absorbs some of the light. The beam then passes through a monochromator and falls on the detector. The amount of an element present in the sample is determined from the amount of the beam which is absorbed as it passes through the flame. Standards are aspirated for each set of analyses to calibrate for the element being measured. Samples of used oil must be diluted in order to be aspirated in this manner.

The advantages of the atomic absorption method for wear metal detection include high sensitivity (ppm range) and low original instrument cost. One disadvantage is that the method determines only one element at a time and specific elements must be known in advance. Oil samples must be diluted, introducing possible dilution errors. In a diluted oil sample, settling of suspended wear particles may lead to false low results. The method is relatively slow in that samples must be prepared, standards run for each analysis, and several analyses performed for several elements of interest.

ENERGY DISPERSIVE X-RAY SPECTROSCOPY

X-ray spectroscopy involves excitation of a sample with an x-ray source. causing the emission of characteristic x-rays from the sample. Voltage signals from a Si (Li) detector are sent to a multi-channel analyzer, then through data reduction to give element concentrations. Samples of oil are poured into sample cups with a mylar or polyproplene film cup bottom. Elements with atomic numbers greater than 11 are simultaneously detected.

Advantages of x-ray spectroscopy include a minimum of sample preparation, speed, and economy of operation. This method also handles suspended wear particles well, as the sample is not diluted. In the case of larger particles which do settle, results will be higher rather than low. Elements such as boron and berylium with atomic numbers lower than 11 are not detected, but other elements including metals, halides, sulfur, and phosphorus are all detected in one determination. The method has relatively low sensitivity, 0.005 percent for sulfur, 10 ppm for iron, but has good accuracy. The method is non-destructive, unlike AA or ES, so small samples may be reused for other tests.

RADIOACTIVE TRACER METHOD

This method was very popular for determining ring wear. Basically, the item to be inspected for wear is sent to a nuclear facility for irradiation. The irradiated parts are assembled into the engine and as the engine wears the removed irradiated material is swept into the lubricating oil. The radioactivity of the oil is measured and a direct correlation to wear can be determined.

Though popular, this method has certain drawbacks when applied to large engines. Irradiating parts as large as cylinder liners is expensive and requires specially built containers for transport from the nuclear facility. The equipment required to measure the radiation level of the oil is expensive. Disposal of large volumes of radioactive oil is a problem. Facilities are needed for proper handling of radioactive materials and monitoring the safety of the test team.

APPENDIX D

PERFORMANCE PLOTS FOR 12-CYLINDER ENGINES UNSTABILIZED ALCOHOL-IN-DIESEL FUEL EMULSIONS

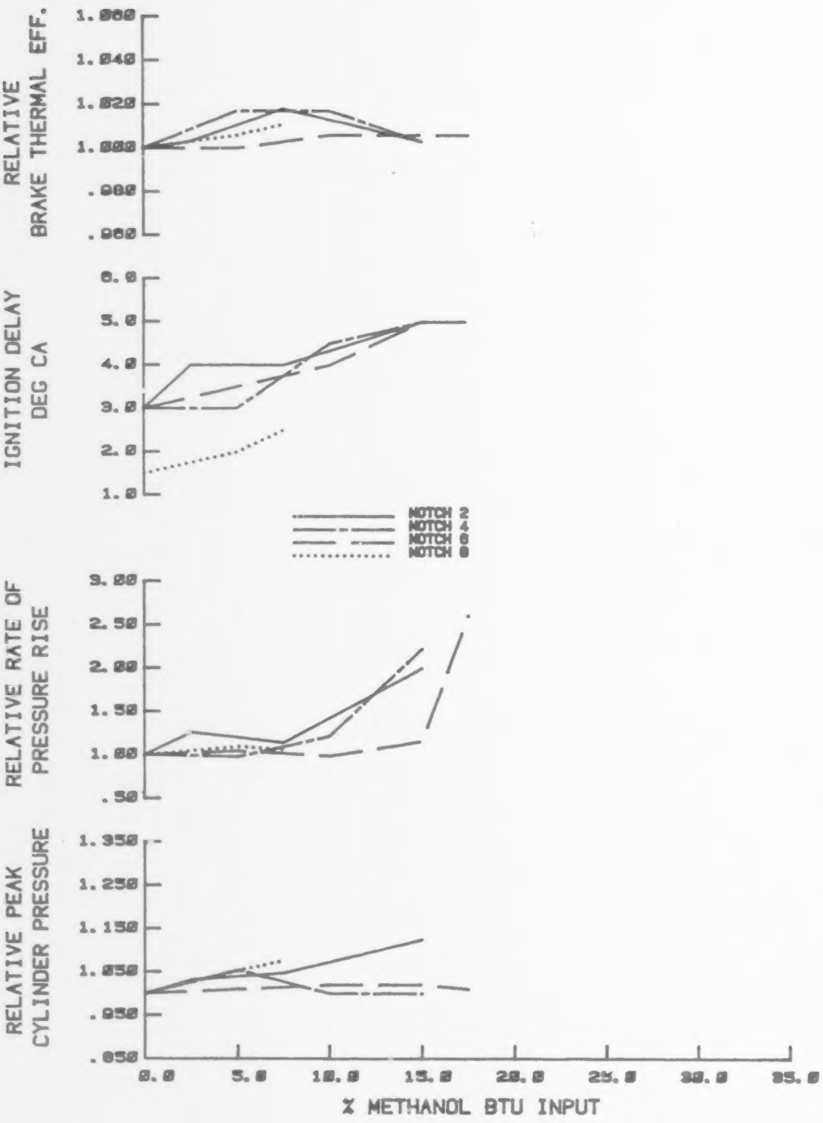


FIGURE D-1 EMD 12-645 E3 ENGINE PERFORMANCE ON METHANOL/DF-2 UNSTABILIZED EMULSIONS

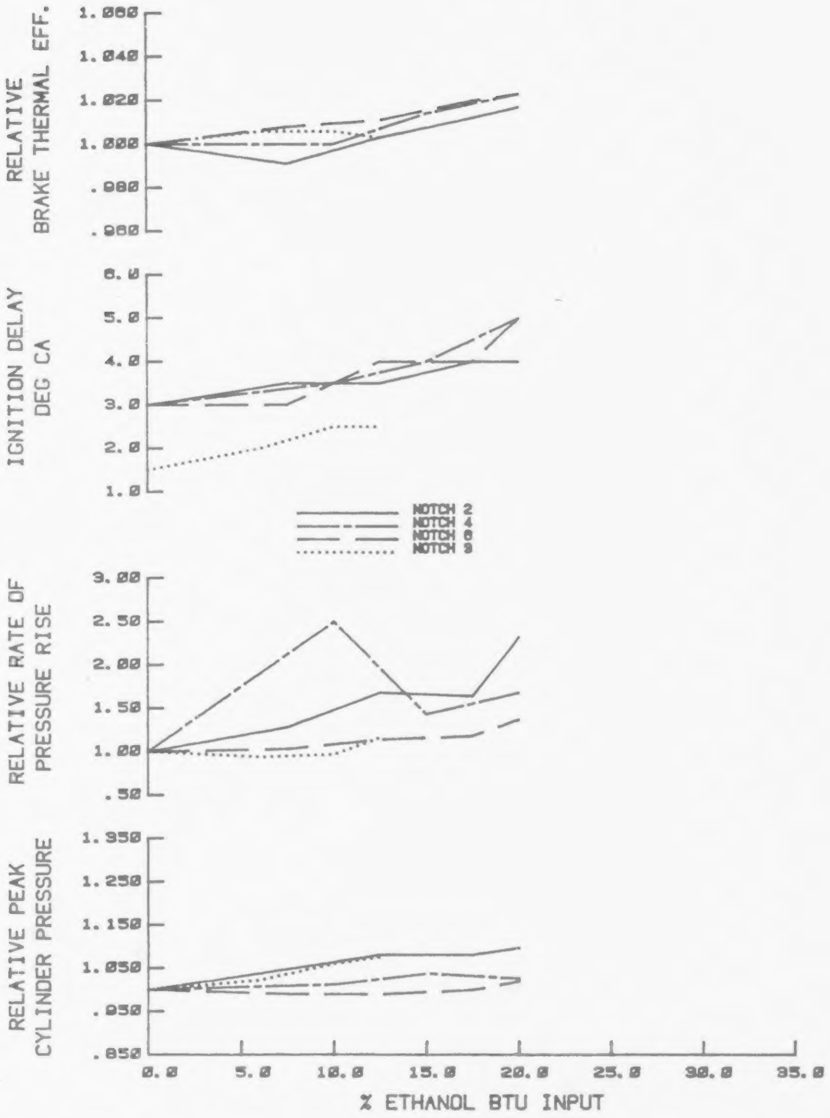


FIGURE D-2 EMD 12-645 E3 ENGINE PERFORMANCE ON ETHANOL/DF-2 UNSTABILIZED EMULSIONS

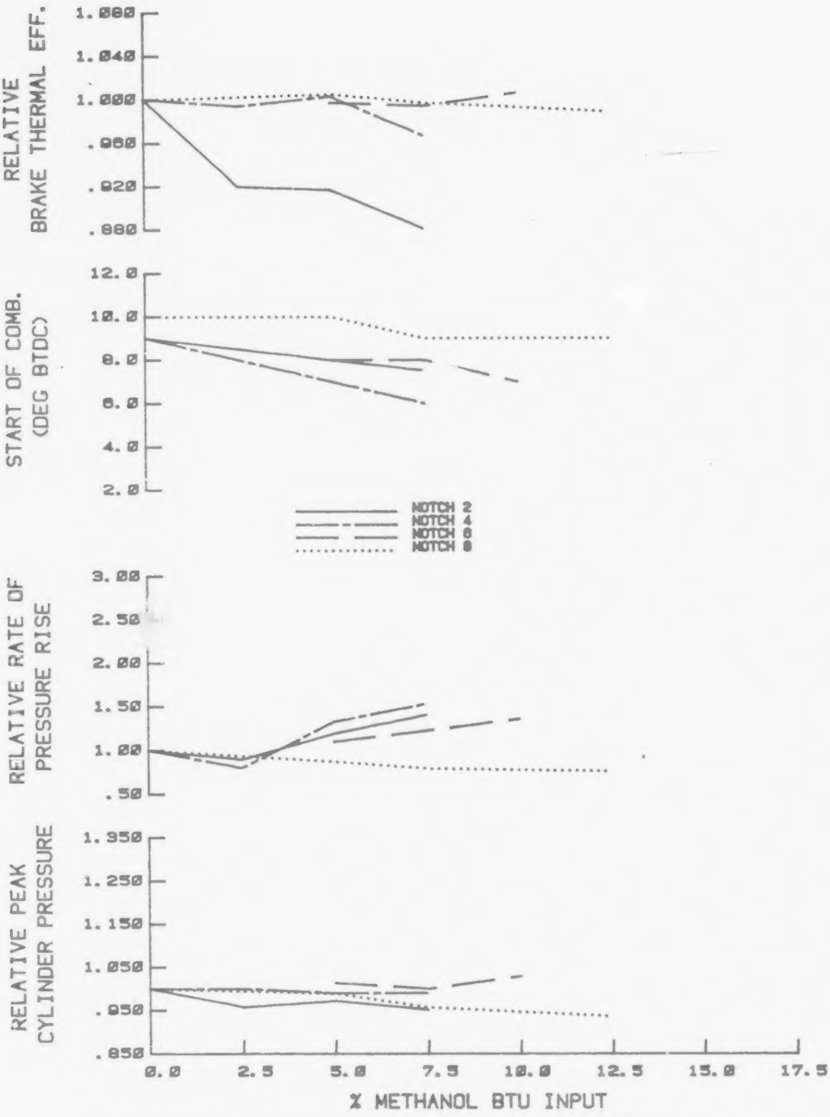


FIGURE D-3 GE 12-7FDL ENGINE PERFORMANCE ON METHANOL/DF-2 UNSTABILIZED EMULSIONS

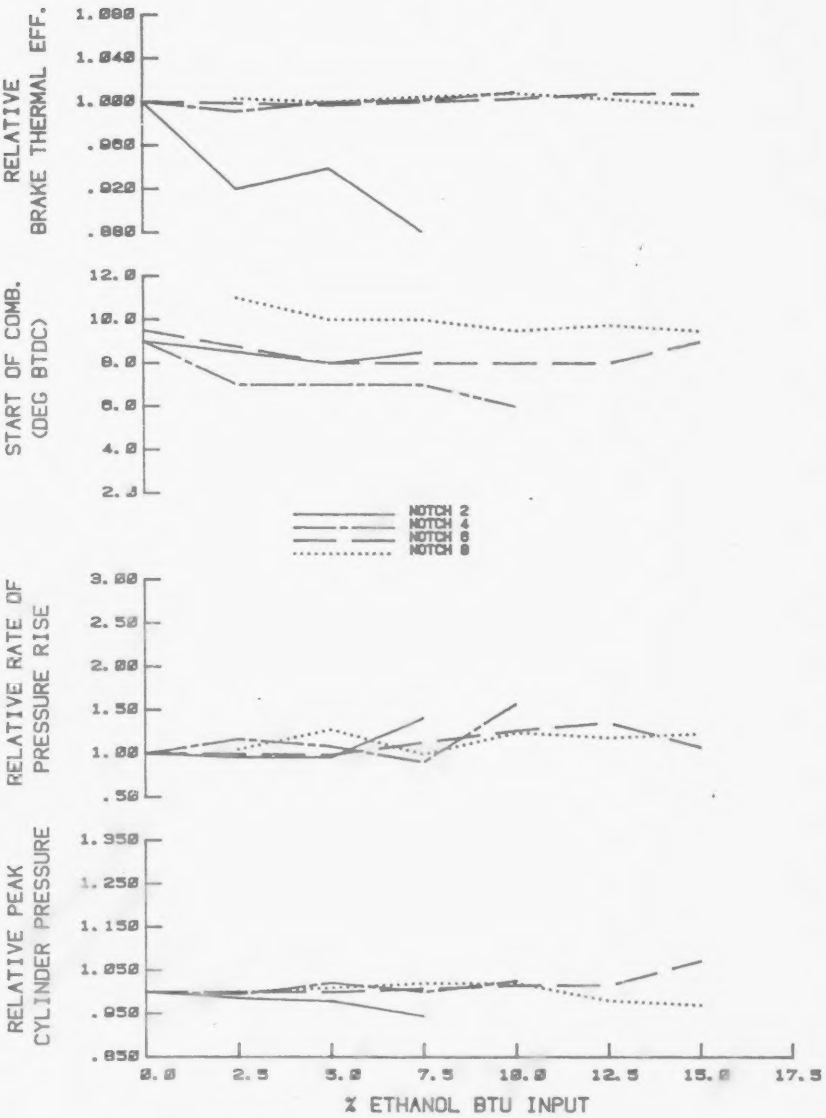


FIGURE D-4 GE 12-7FDL ENGINE PERFORMANCE ON ETHANOL/DF-2 UNSTABILIZED EMULSIONS

APPENDIX E

CYLINDER PRESSURE CHARACTERISTICS, EMD 12-645 E3 OPERATING ON WATER/DF-2 EMULSIONS

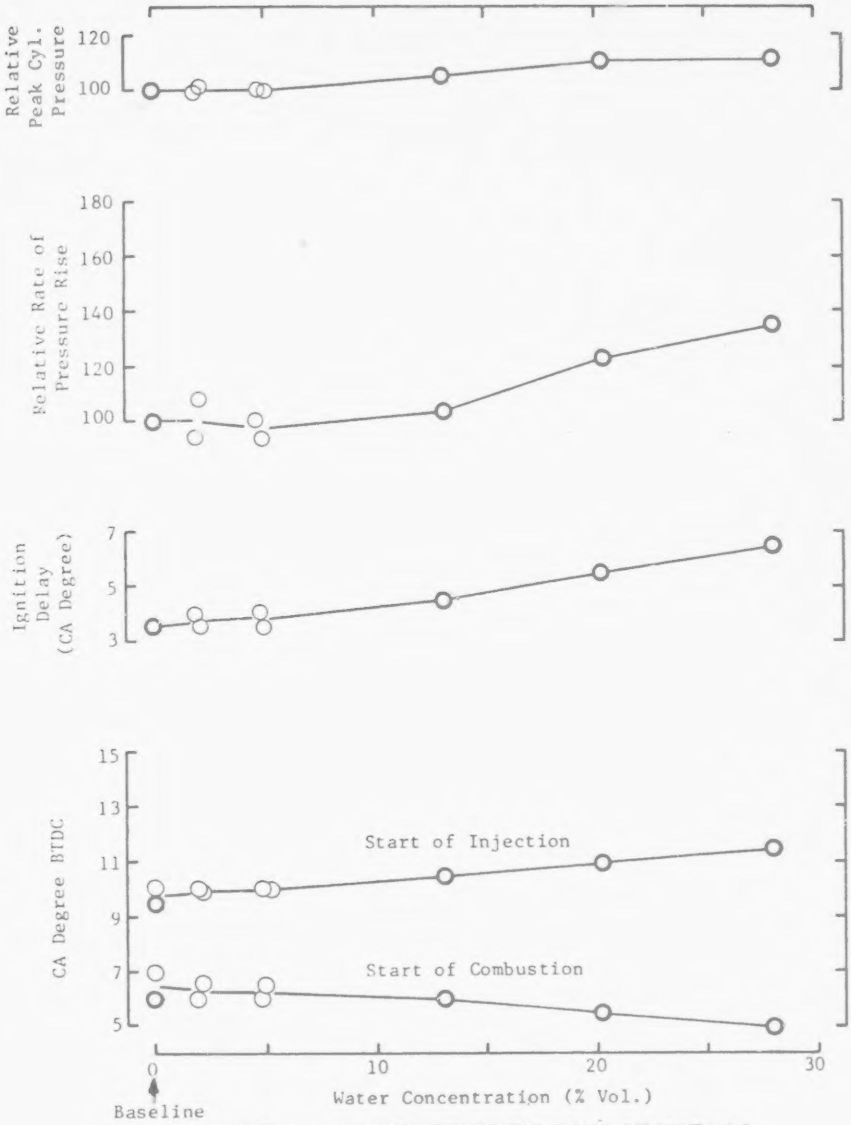


FIGURE E-1 CYLINDER PRESSURE DATA AT NOTCH 2 WATER EMULSION TEST ON EMD 12-645 E3

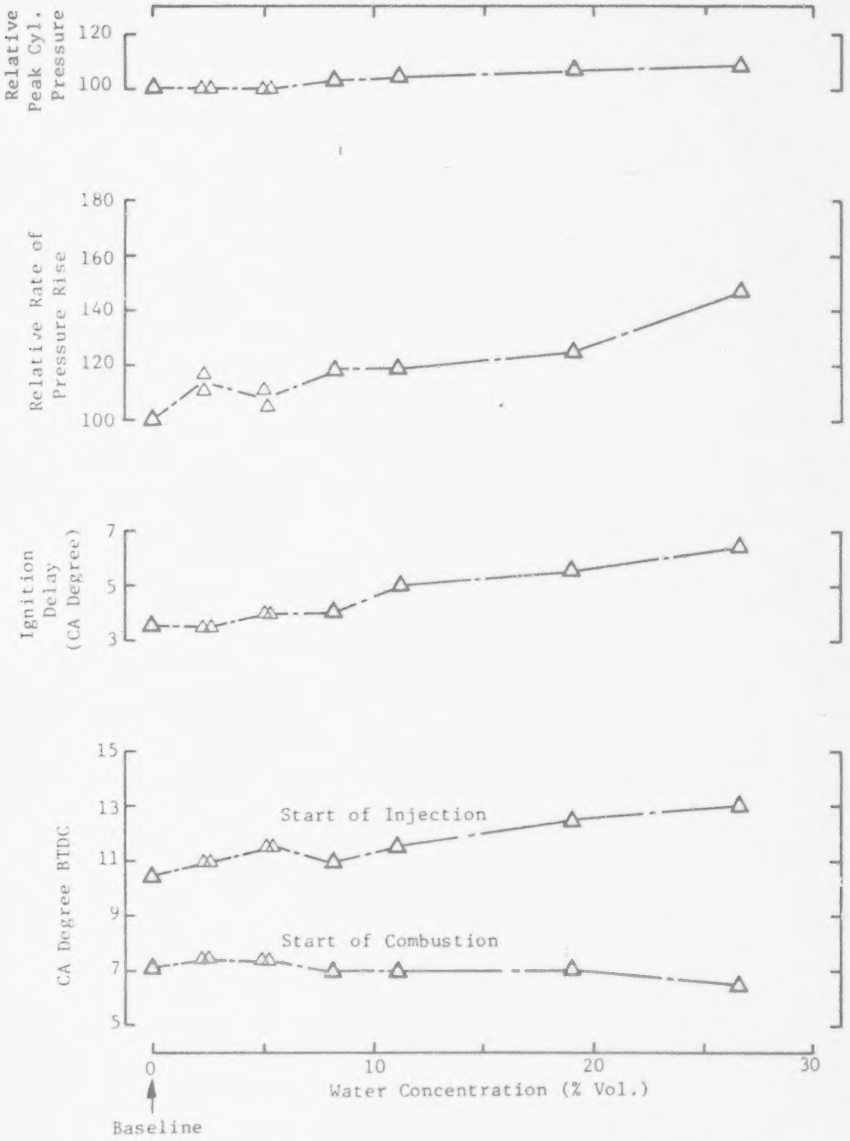


FIGURE E-2 CYLINDER PRESSURE DATA AT NOTCH 4 WATER EMULSION TEST ON EMD 12-645 E3

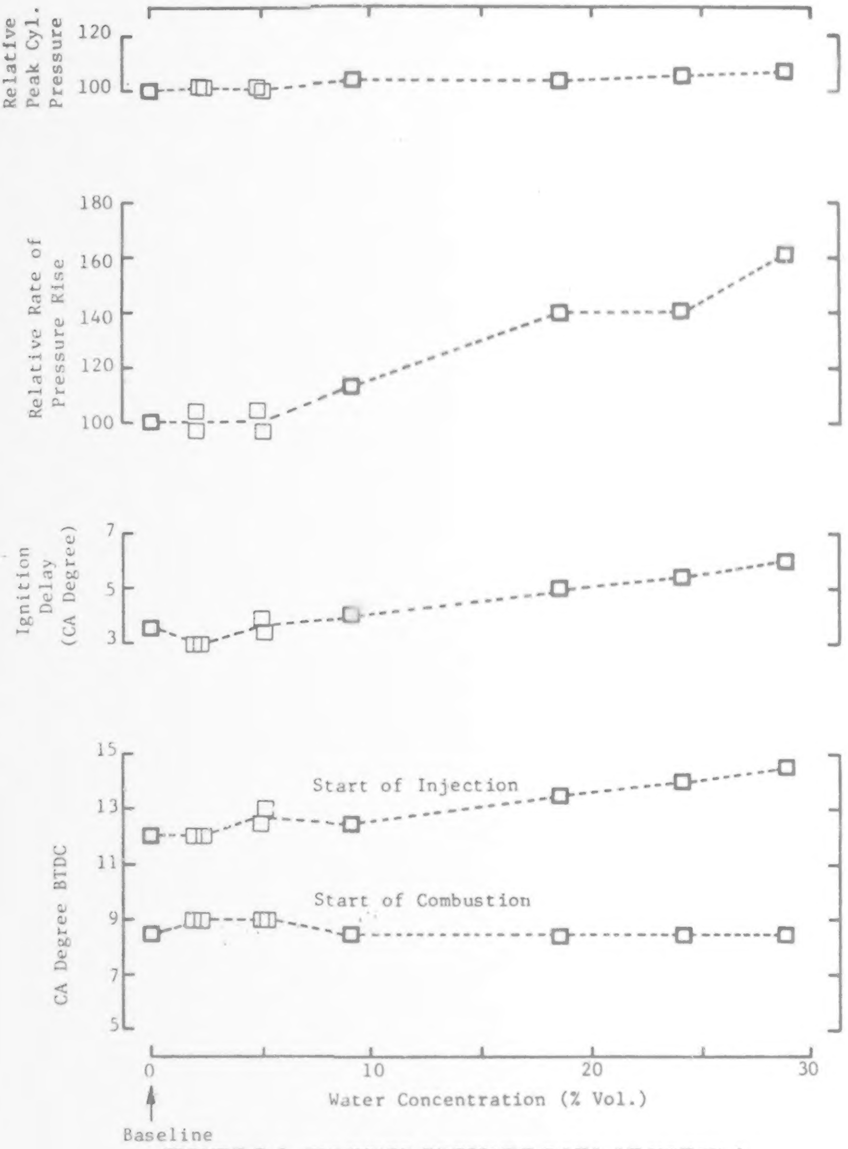


FIGURE E-3 CYLINDER PRESSURE DATA AT NOTCH 6
WATER EMULSION TEST ON EMD 12-645 E3

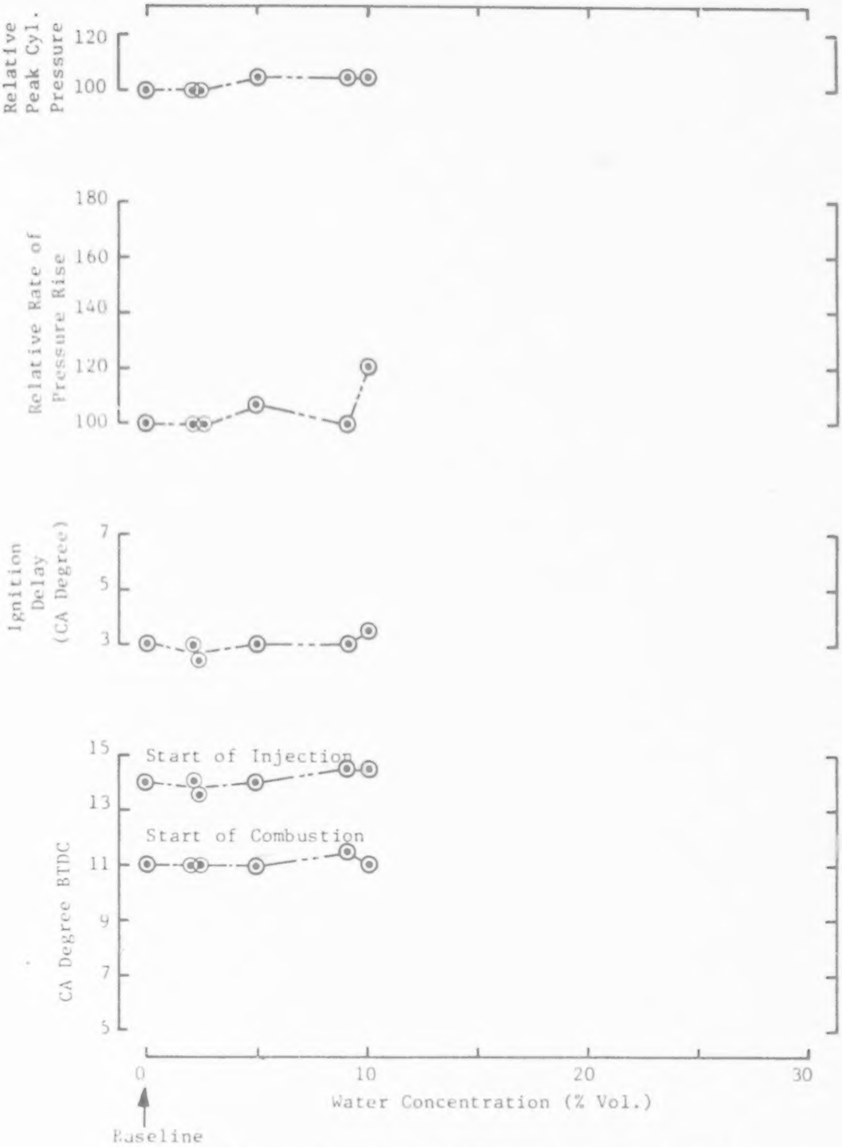


FIGURE E-4 CYLINDER PRESSURE DATA AT NOTCH 8
WATER EMULSION TEST ON EMD 12-645 E3

APPENDIX F

CYLINDER PRESSURE CHARACTERISTICS, GE 12-7FDL OPERATING ON WATER/DF-2 EMULSIONS

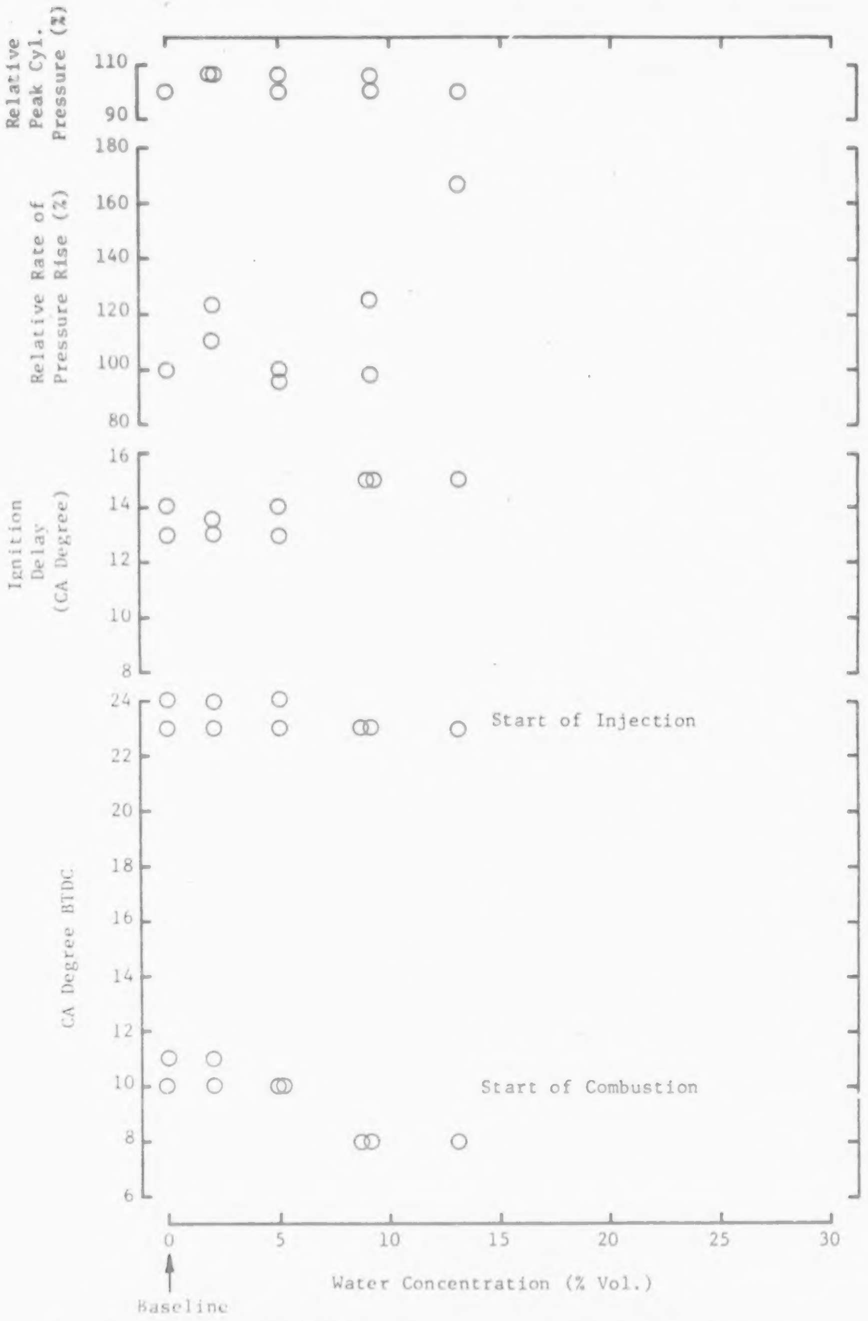


FIGURE F-1 CYLINDER PRESSURE CHARACTERISTICS OF GE 12-7FDL ENGINE OPERATING ON WATER/DF-2 EMULSIONS, NOTCH 2

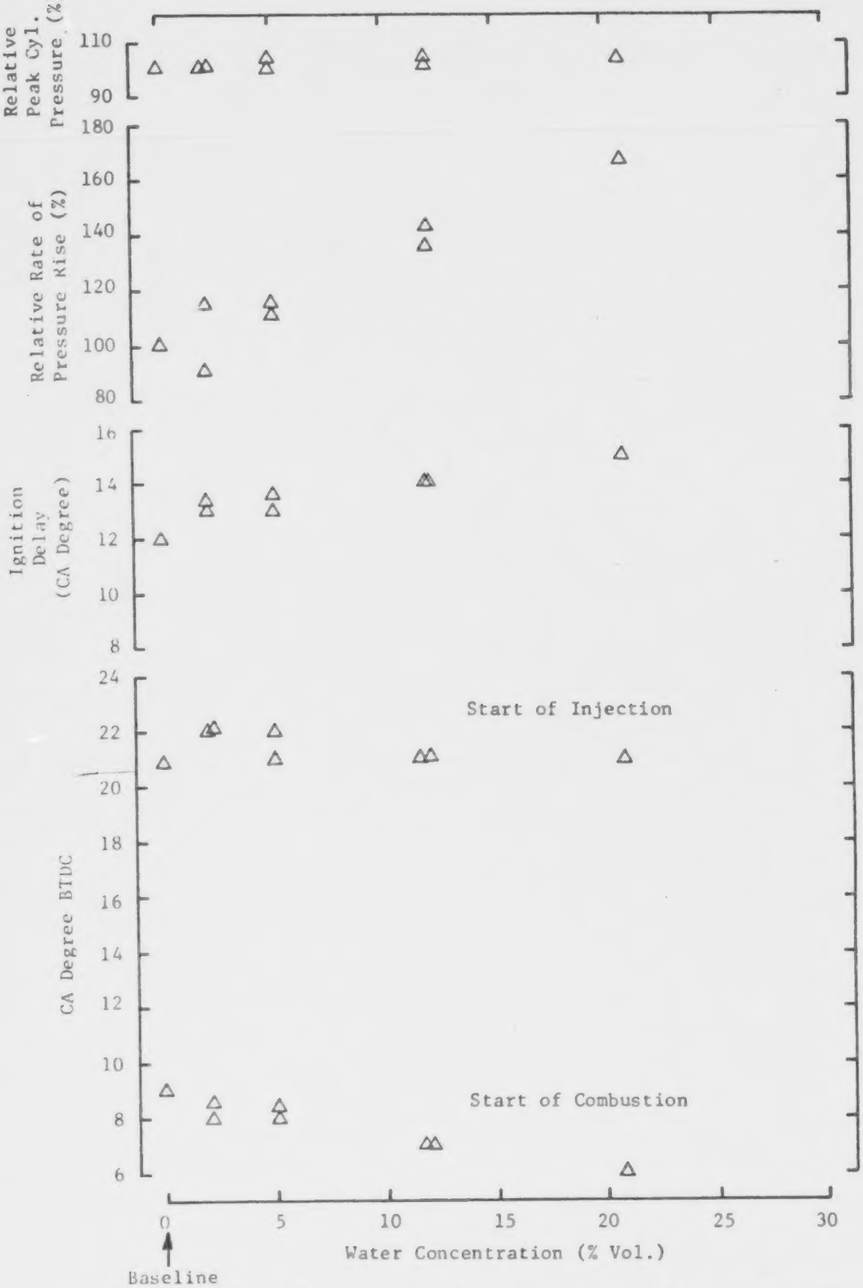


FIGURE F-2 CYLINDER PRESSURE CHARACTERISTICS OF GE-7FDL ENGINE OPERATING ON WATER/DF-2 EMULSIONS, NOTCH 4

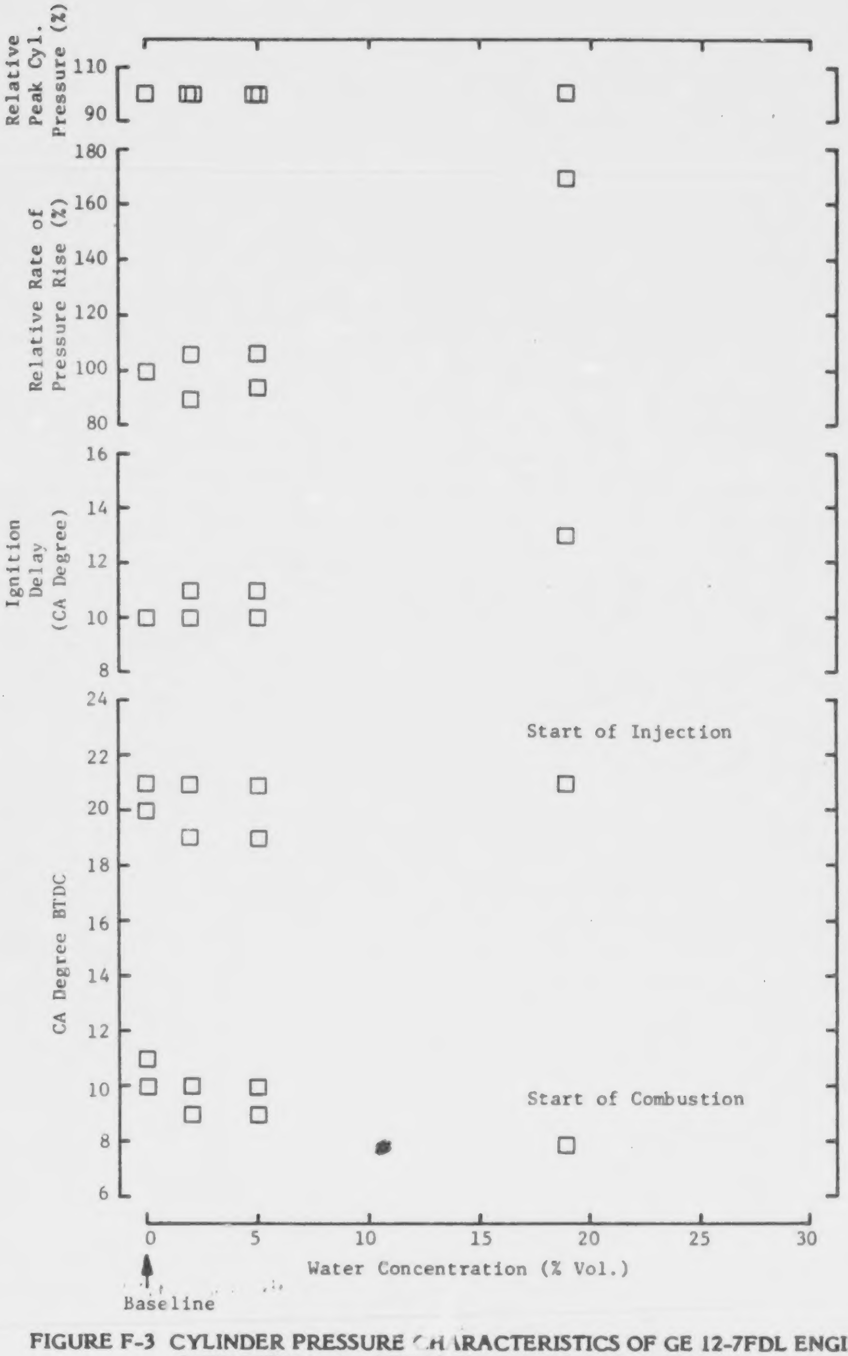


FIGURE F-3 CYLINDER PRESSURE CHARACTERISTICS OF GE 12-7FDL ENGINE OPERATING ON WATER/DF-2 EMULSIONS, NOTCH 6

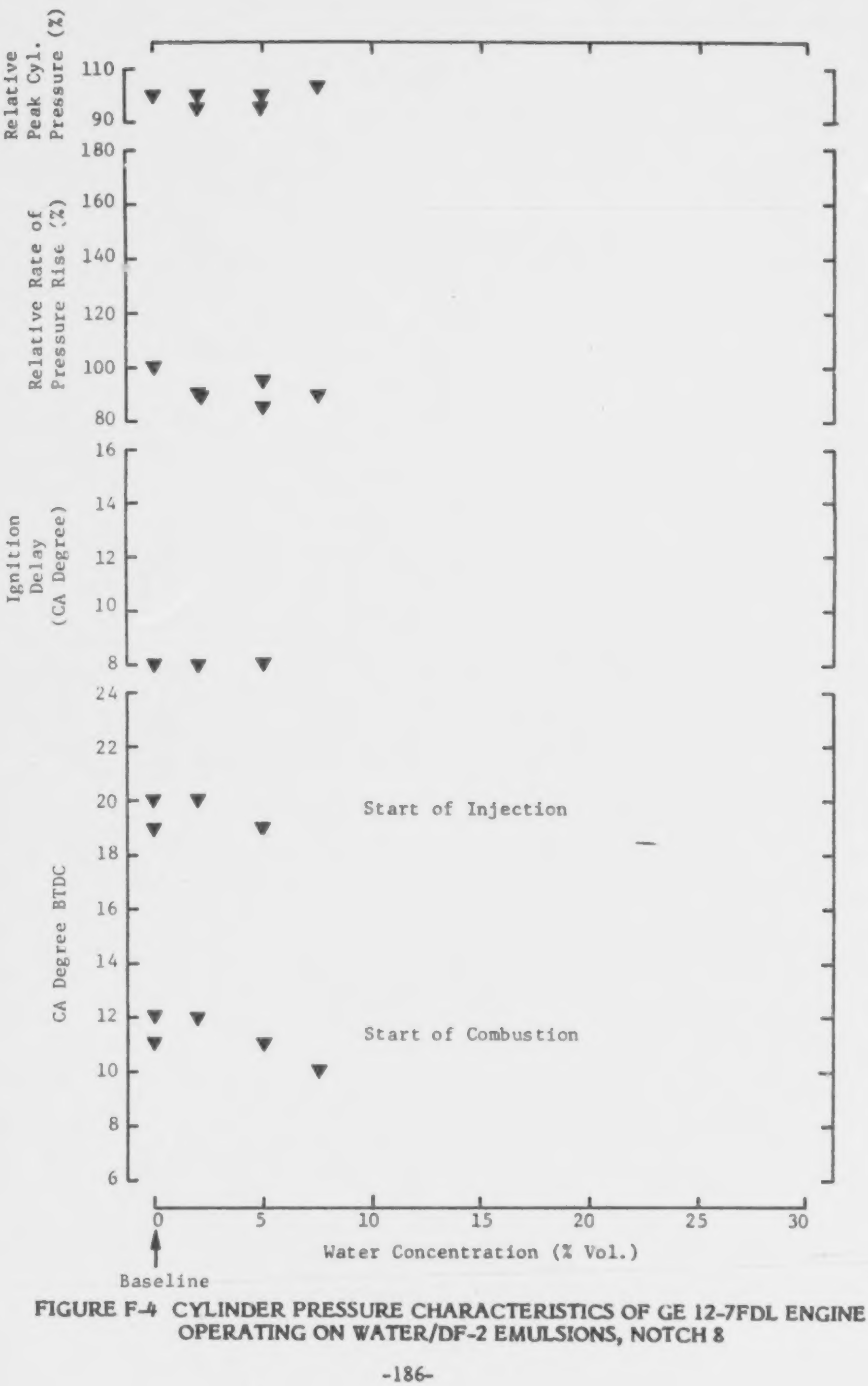


FIGURE F-4 CYLINDER PRESSURE CHARACTERISTICS OF GE 12-7FDL ENGINE OPERATING ON WATER/DF-2 EMULSIONS, NOTCH 8

AAR REPORT 505

TECHNOLOGY ASSESSMENT:

COAL AS A RAILROAD FUEL

JOHN T. STONE, JR.

ASSOCIATION
OF AMERICAN
RAILROADS

RESEARCH AND TEST DEPARTMENT

WASHINGTON, D.C.

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15. Abstract (711A2)

The state of coal liquefaction and utilization technologies which could allow coal to be used as a source of energy for railroads is reviewed. There appears to be no quick or inexpensive way for the railroad industry to begin utilizing coal as a primary fuel.

Three types of liquefaction processes are reviewed: pyrolysis, direct hydrogenation, and indirect liquefaction. Several versions of each type of process are discussed in non-technical terms. The potential use of liquid coal products in current railroad diesel engines, as well as other types of prime movers, is discussed.

Combustion of solid coal, coal-oil, and coal-water mixtures in steam engines and gas turbines is reviewed. In addition, a short discussion of stationary electrical generation is included.

16. Subject Terms (621A3) Coal, coal liquefaction, diesel fuel, toxicity, coal mixtures, diesel engines, steam engines, gas turbines, Stirling engines, electrification, fuel cells.	17. Availability Statement (341A3) James G. Britton Office of the Director AAR Technical Center 3140 S. Federal St. Chicago, IL 60616

FOREWARD

This report is intended to be a general reference document on coal-based fuels and their application as fuel for possible railroad locomotive designs. Technical and commercial feasibilities of each coal product are presented for the present time and during the next 10 to 15 years.

This report is not a primary decision-making tool for railroad managers. It does not present economic comparisons between the present petroleum fueled diesel electric locomotive and the various coal-based fuels powering diesels or other types of engines. Nor does it rank-order the probabilities of commercial availability of each fuel and locomotive prime mover.

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EXECUTIVE SUMMARY

This report provides a review of coal liquefaction technology and its future utilization by U.S. railroads. It was found that no way exists for U.S. railroads to use coal as a primary locomotive fuel in the immediate future. Coal is neither economically nor commercially feasible as a fuel source for diesel electric locomotives. Short of a massive capital commitment to produce coal liquids or an alternative shift to steam powered locomotives or electrification, coal is not a viable fuel option at the present time.

Only one commercially available coal liquefaction process, the Fischer-Tropsch process, produces a fuel completely compatible with existing diesel locomotives; however, the only Fischer-Tropsch plants operating today are located in the Union of South Africa.

Although a number of commercial processes are available for making methanol from coal, current technology for using methanol in a diesel engine would require dual-fueling with diesel fuel. Three other coal liquefaction processes, Solvent-Refined Coal (SRC), Exxon Donor Solvent (EDS), and H-Coal, have been developed to an advanced stage , but have not yet been demonstrated on a commercial scale. These processes produce liquid fuels that could be used in a locomotive diesel engine by dual-fueling, blending with conventional diesel fuel, or further upgrading the fuel until it has the same characteristics as petroleum-based fuel.

The fuels from the Fischer-Tropsch or methanol synthesis processes are expected to be no more toxic than similar petroleum-based fuels. Possible toxicity of intermediate products from SRC, EDS, or H-Coal processes could be reduced to a level similar to petroleum-based products by known upgrading methods.

Improved steam-powered locomotives could be fired directly with coal or coal mixtures. Readoption of the coal-fired steam locomotive, however, would require new operating, maintenance, and fueling procedures and facilities. The development of other new prime movers such as the fuel cell, open- and closed-cycle gas turbines, Stirling engines, or advanced diesels that could operate on coal or coal-derived liquids or mixtures may present U.S. railroads with a variety of choices in the future. Electrification also remains a technically feasible alternative.

A likely schedule for these developments follows:

New U.S. Technology	Earliest Expected Time
Fischer-Tropsch facilities	Mid-1980's
Methanol synthesis facilities	Mid-1980's
Improved steam engines	Mid-1980's
Other advanced engines	Late 1980's
SRC, EDS, H-Coal facilities	Late 1980's
Coal mixtures	Late 1980's
Fuel Cells	Mid-1990's

Through the mid 1980s, coal-based fuels are likely to be more costly in operating and maintenance cost than petroleum-based fuels. But at some future time, because of the eventual relative scarcity of petroleum, and its concurrent high price, coal-based technology, provided it is environmentally acceptable, may become an economic necessity.

There is a high probability that petroleum - particularly middle distillates - will be scarce and relatively more expensive in the future. Coal-based fuel technology is constantly improving and coal-based fuels may become economically competitive by the late 1980's or later.

PART I. INTRODUCTION

The disruption in supplies and skyrocketing cost of petroleum products during the 1970's resulted in a worldwide scramble for cheaper, more reliable energy sources. In the railroad industry, stockholders and managers of railroads, in particular those that own or have access to coal, would like to know whether coal or coal products could be used to power trains. This report is intended to describe the state of the art for use of coal products as fuel for railroad prime movers or for power sources of electrified railroad systems.

This report describes various coal products, their production processes, and their applicability as railroad fuels. It surveys the technology existing in the early 1980's, including brief discussion of the economics of coal products as replacements for petroleum.

Part II of this report describes currently available coal products and their manufacturing processes. Other processes that are in the design stage are also identified. The appendix discusses further details about the processes.

Part III covers the applicability of coal products as fuel for railroad prime movers in use or under development and for railroad electrification.

1. SCOPE

The purposes of this assessment are to -

- Identify the coal processing technologies and explore their readiness to provide the energy for operating the nation's railroads.
- Identify the compatibility of coal and coal-based fuels with existing railroad locomotives, fuel delivery systems, and operations.
- Provide an overview of the environmental, health, safety, and economic factors involved in using coal and coal-based fuels.
- Suggest actions to be taken by the Association of American Railroads and member companies of the industry to further evaluate options and to move toward coal as a primary energy source.

The study does not attempt to exhaustively review prime mover technology or provide economic and operational analyses of the use of coal or coal-derived fuels for application by the railroad industry.

2. BACKGROUND

The susceptibility of the U.S. economy to damage from increases in energy prices and disruptions of the oil supply has been emphatically demonstrated. Prices of petroleum products have increased about 10-fold since 1973. The disruptions of the supply of imported oil that occurred in 1974 and 1979 caused allocation problems of the fuels used by agriculture, trucking, and rail transportation. After the latest major price increase occurred in 1979, prices failed to stabilize until fall of 1981. Even though prices are currently stable or decreasing slightly, it is generally expected that world oil prices will continue to rise in the long term. Despite these gloomy economic prospects, in 1981 oil still represented about 40 percent of all the primary energy consumed in the U.S.

In summary, the events of the recent past have illustrated several facts:

- Oil (and readily available substitute fuels) will continue to become more expensive over the long term.
- Oil supplies from foreign sources are uncertain because of historical instabilities, political factors, and the potential for external intervention.
- Even though significant steps have been made to reduce energy consumption and to increase domestic production, the economy will continue through the 1980's to be vulnerable to serious damage from disruption of the imported oil flow.

Recognizing this vulnerability, the Association of American Railroads commissioned this study to review technologies that might allow the nation's railroads to return to the use of coal as a primary energy source. Although coal is the most abundant fossil fuel energy resource in the U.S., domestic coal presently supplies only one-fifth of the primary energy used. The price advantage per Btu of coal over oil has widened rapidly during the past decade. Furthermore, several of the railroad companies own substantial coal reserves, which could assure them a future supply of coal-based fuel.

3. COAL AS A RESOURCE

There are two significant characteristics about the coal resource base of the U.S.: (1) its magnitude, and (2) its wide variability (in type and quality).

The demonstrated coal reserves in the U.S. are 438 billion tons (900 billion barrels of oil equivalent), over half of which is estimated to be recoverable with available mining techniques. About two-thirds of this demonstrated reserve is in deposits recoverable by underground methods. Bituminous coal represents about 54 percent of the reserves, subbituminous 38 percent, lignite 5 percent, and anthracite approximately 2 percent (see Table 1). In addition, there are also 120 billion tons of peat (averaging 35 percent moisture content) that are not counted in the coal resources and reserves.

In addition to the demonstrated coal reserves, there may be an additional 1,100 billion tons (2,300 billion barrels of oil equivalent) of inferred, thin-seam, and undiscovered resource that may be recoverable through advanced technologies, including improved mining methods or underground coal gasification.

As can be seen in Figure 1, the U.S. coal reserves are located in many regions of the country. Bituminous coal is found principally in the Appalachian, Midwest, and West-Central regions, subbituminous in the Western Great Plains and Southwest regions, and lignite in the Eastern Great Plains and Gulf regions. Anthracite is located mainly in the state of Pennsylvania.

Coal is highly diverse in its properties, leading to a need for a menu of technologies for effective utilization of the resource base. Coals are broadly classified by rank, a classification system that reflects general characteristics of coal deposits as they change over geological time. The lowest rank coal, namely lignite, is the youngest. The rank then increases through subbituminous and bituminous to anthracite and metaanthracite. As the rank changes, the physical properties of the coal change, e.g., as coalification proceeds, moisture and oxygen are driven out of the coal, resulting in a gradual increase in heat content from a low of 6,000 Btu/lb

Table 1
DEMONSTRATED U.S. COAL RESERVES BY REGION AND COAL RANK[a,b]
(million tons)

Region	Location	Coal Rank				Subtotals	
		Bituminous	Subbituminous	Anthracite	Lignite	By Location	By Region
Appalachia	Surface	18,794	-	143	1,083	20,020	
	Deep	84,498	-	7,104	-	91,602	111,622
Midwest	Surface	26,108	-	8	3,208	29,324	
	Deep	75,089	-	89	-	75,178	104,502
West	Surface	1,951	60,686	-	28,900	91,537	
	Deep	22,271	107,722	28	-	130,021	221,558
Subtotals	Surface	46,853	60,686	151	33,191	140,881	-
	Deep	181,858	107,722	7,221	-	296,801	-
	Totals	228,711	168,408	7,372	33,191	437,682	437,682

---

[a] Measured and indicated deposits, half of which may be considered "recoverable" and are so designated.

[b] Demonstrated reserves potentially mineable as of January 1, 1976.

Source: Coal Data Book, The President's Commission on Coal, Washington, D.C., February 1980.

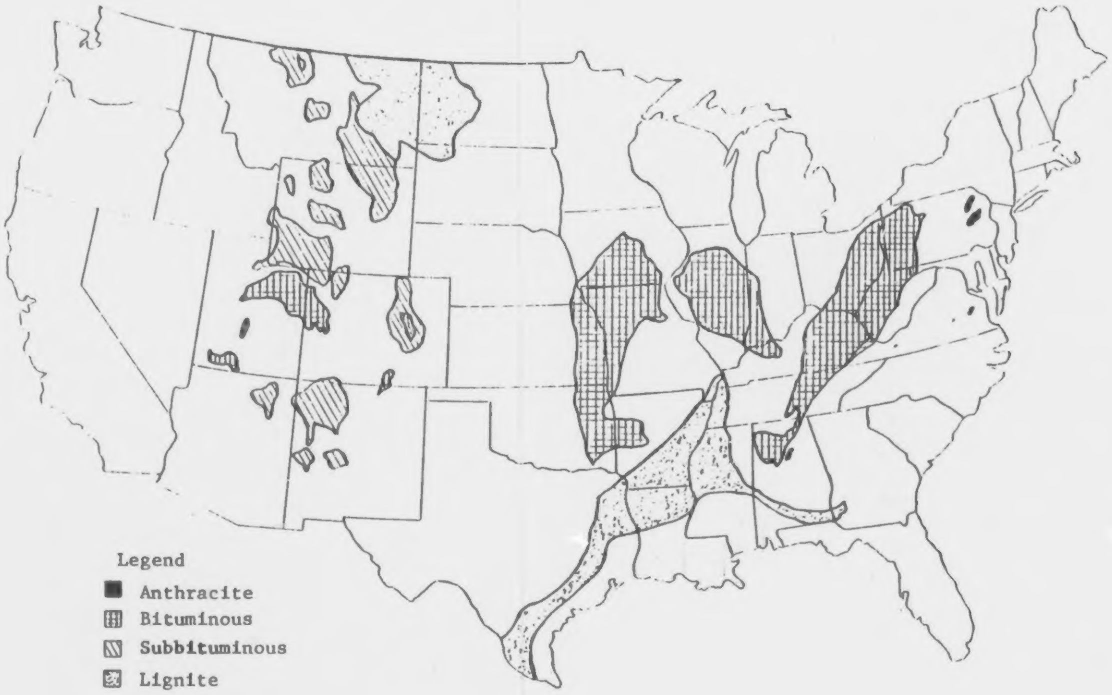

Figure 1. Coal Reserves in the Continental United States

(for moist, mineral-matter-free lignite) to over 16,000 Btu/lb (for anthracite). Some of the important chemical and physical properties of U.S. coals of different ranks are presented in Table 2. The variations of these properties and caking characteristics require that coal conversion and utilization processes be more or less specifically designed for particular coals.

U.S. coal production has been relatively stable at 600-700 million tons/year for the last two decades. It is only in the last few years that there are signs of both increased mining capacity and increased production. Depending on the estimate, production is projected to be 1 to 1.5 billion tons/year by 1990. DOE projections of future coal use are shown in Table 3.

Table 2
Selected Properties of
U.S. Coals of Different Ranks

	Lignite	Subbituminous	Bituminous	Anthracite
Moisture capacity (wt%)	40	25	10	5
Carbon[a] (wt%)	69	75	83	94
Hydrogen[a] (wt%)	5	5	6	3
Oxygen[a] (wt%)	24	19	10	3
Volatile Matter[a] (wt%)	53	48	38	6
Aromatic C/total C ratio	0.70	0.78	0.84	1.0
Density (g/cc)	1.4	1.4	1.3	1.5
Heat content (Btu/lb)	11,600	12,700	14,700	15,200
Rank heat content (Btu/lb)[b]	6,000-8,000	8,000-11,500	11,500-14,000	14,000-16,000

[a] Dry, mineral-matter-free basis.
[b] Moist, mineral-matter-free basis.

Source: ERCO Low-Rank Coal Study, U.S. DOE, GFETC Contract No. DE-ALIS-79FC10066, November 1980, Table 2-1-7.

Table 3
Projected Coal Use

Industry	1980	1990		2000		2020	
	MT/Y[a]	MT/Y	Range	MT/Y	Range	MT/Y	Range[b]
Direct Use (Industrial and Other)	135	230	210-265	310	275-340	321	-
Utilities (Electric generation)	570	784	690-900	1029	840-1165	1061	-
Existing units[c]	(570)	(520)	-	(485)	-	-	-
Oil/Gas conversions to coal[c]	0	(34)	-	(34)	-	-	-
New coal-fired capacity[c]	0	(230)	(135-645)	510	(320-645)	-	-
Direct & Utilities Subtotal	705	1014	900-1165	1339	1115-1505	1382	-
Synfuels (coal used)							
Liquids	0	30	15-65	190	95-290	-	-
Gases	0	30	10-45	95	40-125	-	-
Synfuels Coal Use Subtotal	0	60	25-110	285	135-415	1578	-
Net Exports							
Metallurgical coal	65	70	55-75	70	60-80	-	-
Steam coal	25	75	40-105	180	80-280	-	-
Exports Subtotal	90	145	95-180	250	140-360	288	-
Total	795	1219	1020-1455	1874	1390-2280	3248	-

[a] Million Tons Per Year.

[b] Data not available.

[c] Because some data were not available, figures for the categories of utilities were placed in parentheses.

Source: Extracted from Table 7-1, Energy Projections to the year 2000, DOE/DE-0029, July 1981.

PART II. COAL PRODUCTS AND PRODUCTION PROCESSES

Like petroleum, coal is a versatile fuel. Although coal can be used as it comes from the ground, a rough "refining" - removal of dirt and rock - improves its usefulness. But coal can also be further processed into other solid, liquid, and gaseous forms. Some of the processes result in two or more products. The more complex and energy intensive the process, the more expensive the resulting products will be. Unfortunately, heavily refined products are usually required for powering internal combustion engines.

Solid products include lump coal, pulverized coal, and carbon black. Liquid products include distillates, gasoline, methanol, and coal tars. Gaseous products include methane and naphtha.

1. SOLID COAL PRODUCTS

Solid coal, used as a fuel for centuries, became the primary fuel for railway locomotives in the mid-19th century, continuing until the mid-20th. Solid coal is used in lump form or pulverized to facilitate combustion. It is converted to almost pure carbon by further refinement.

2. Coal and Liquid Mixtures

Coal and liquid mixtures have a potential for reducing consumption of oil-based liquid fuels. Coal-oil mixtures (COMs) have already been demonstrated as extenders for oil in industrial and utility boiler applications. With similar applications in mind, coal-water mixtures (CWMs) are also being developed.

2.1 Coal-Oil Mixtures

The COM concept, first proposed in 1929, consists of preparing a mixture of liquid fuel oil and pulverized coal. Mixtures with fractions of coal up to 50 percent by weight have been successfully fired in industrial and utility oil-fired boilers. The COM preparation technology is considered to be commercially available; several facilities for the production of COMs are being constructed to serve the industrial market. When including the costs of the preparation plant, use of a COM can result in 25 percent savings per Btu over the use of pure oil.

2.2 Coal-Water Mixtures

The newer CWM technology is expected to achieve commercial readiness in 5 years. Similar to COM in many respects, CWM will draw on the same technology base during development. Although mostly coal (70 percent), a CWM can be stored, handled, and transported like fuel oil.

For several years, Atlantic Research Incorporated has been developing CWMs, under contract to the Pittsburgh Energy Technology Center. In addition, Sconiaiventor, Gulf and Western, and Alfred University have developed processes for producing CWMs. The best composition is approximately 70 percent pulverized coal, 29 percent water, and 1 percent emulsifying agent by weight. Combustion testing in a boiler designed for fuel oil has shown that CWMs can be fired satisfactorily. DOE also plans to test the CWM in diesel engines and in combustion turbines. These tests should be completed in 1982. The total cost of preparing a low-sulfur CWM is estimated (1981) to be approximately $3.20 per million Btu (approximately $0.45/gal).

3. Coal Liquefaction Processes

Coal has been liquefied and used as a fuel for most of the 20th century. The majority of the experiences in commercial production have been in countries that could not obtain enough petroleum products to maintain industrial efforts, as in the Union of South Africa, or war efforts, as in Germany during World War II. Where petroleum is easily available, the cost of producing liquefied coal products is prohibitive. For this reason, there are no commercial coal liquefaction plants currently operating in the U.S.

Liquefied coal can include a wide range of possible products roughly equal in number to those obtainable from petroleum, but unlike petroleum refining, each coal liquefaction technique produces a well-defined slate of products. Although most of the processes proposed in recent years in the U.S. have been intended to make gasoline or methanol, some can lead to the production of a synthetic middle distillate replacement for No. 2 diesel fuel.

As a result of the Alternative Fuels Production Act of 1980 (P.L. 96-126) and the Energy Security Act of 1980 (P.L. 96-294), a number of commercial-scale coal liquefaction plants are being proposed for deployment in the U.S. The Energy Security Act of 1980 established a national goal of 500,000 BOE (Barrel of Oil Equivalent - 42 gallons per barrel) production by 1987. The act also provided approximately $20 billion of incentives in the form of loan guarantees, price guarantees, and joint ventures with the nation's industrial complex. Achievement of the production goal is to be accomplished by industry with support as necessary from the Synthetic Fuels Corporation, established in 1980 under the Energy Security Act.

Industry responded to both an Alternative Fuels Production Act solicitation issued in August 1980 and Synthetic Fuels Corporation solicitations issued in January 1981 and May 1982 with proposals for numerous synthetic fuel production facilities. Of interest in this assessment are those which produce liquid products from coal. Table 4 provides a summary description of the proposed coal liquefaction plants as of July 1982. The combined total annual production of liquid products from all of these proposed plants follows:

Product	Amount (BOE/day)
Direct-hydrogenation liquids	25,000
Fischer-Tropsch liquids	106,000
Methanol	220,000
Gasoline	171,000
Total (proposed)	522,000

This is the potential production by the end of 1989. With the deemphasis on Government involvement in energy research by the current administration, some of these proposed plants will be cancelled or postponed.

The remainder of Part II briefly describes coal liquefaction processes, identifying the leading commercial techniques associated with each type. (More technical information on each technique is provided in the appendix.) In addition, there is a discussion of the likely cost and environmental and safety issues of producing and using coal liquids.

Table 4

COAL LIQUEFACTION PLANTS PROPOSED UNDER ALTERNATIVE FUELS PRODUCTION ACT AND ENERGY SECURITY

Synthetic Product	Sponsor	Site	Process	Potential Production (BOE/day)	Start-up	Status
Methanol acetic anhydride	Tennessee Eastman	Kingsport, TN	Texaco		1983	Private construction to begin 1980.
Methanol	Dakota Co.	Dunn, MD	Lurgi; Lurgi methanol synthesis	40,000	1982	Feasibility study; construction to start 1982.
Methanol	Cook Inlet Region Inc.	Granite Point	Winkler; ICI	54,000	1989	Feasibility study, loan guarantee, and price guarantee requested from SFC under second solicitation.
Methanol	W.R. Grace	Moffat Co., CO	K-T	14,000	-	Feasibility study awarded.
Methanol	Houston Natural Gas; Texaco	Covent, LA	Texaco	11,400	-	Feasibility study awarded; loan guarantee proposed to SFC. Dropped.
Methanol	AMAX, Inc.	Duluth, MN	K-T or Texaco	6,800	-	Feasibility study.
Methanol	Wentworth Brothers; 19 Utilities	Western N. Dak.	-	93,000	-	Preliminary study.
Methanol	Celanese Corp.	Bishop, TX	-	10,000	-	Feasibility study to be completed 1981.
Methanol	MAPCO Synfuels; Fuels Inc.	Carmi, IL	Texaco; low-pressure methanol synthesis	18,000	-	Price support and loan guarantee proposal to SFC under second solicitation.
Methanol	EG&G	Fall River, MA	Texaco	9,500 13,000	- -	Loan guarantee requested from SFC under second solicitation.

Table 4 (cont.)
COAL LIQUEFACTION PLANTS PROPOSED UNDER ALTERNATIVE FUELS PRODUCTION ACT AND ENERGY SECURITY

Synthetic Product	Sponsor	Site	Process	Potential Production (BOE/day)	Start-up	Status
Methanol	Energy Transition Corporation	Moffat Co., CO	KBW	17,000	-	Price guarantee requested; plans to expand to 17,000 BOE/day. Changed to hydrogen production, May 1982.
Methanol	Energy Transition Corporation	Grants, NM	-	1,700	-	Price guarantee requested from SFC. Dropped.
Methanol	Energy Transition Corporation	Creswell, NC	KBW (Peat gasification)	3,700	1984	Price guarantee requested from SFC. Project in Phase II under SFC.
Methanol	Westinghouse	Cambria and Somerset Cos., PA	Westinghouse	13,300	1987	Loan and price guarantee requested from SFC under second solicitation.
Methanol	Energy Synfuels Associates	Emery Co., UT	Lurgi	13,000	-	Loan guarantee requested from SFC. Dropped.
Fischer-Tropsch liquid, SNG, chemicals	Texas Eastern Corp.	Henderson, KY	Lurgi; Fischer-Tropsch	56,000	-	Cooperative agreement under DOE alternative fuels program.
Fischer-Tropsch liquid	Occidental Petroleum	-	Fischer-Tropsch	50,000	-	Feasibility study.
Gasoline	Hampshire Energy Co.	Gillette, WY	KBW; Lurgi; Mobile MTG	19,000	1986	Feasibility study awarded; price and loan guarantees requested from SFC. Project is in Phase II under SFC.

Table 4 (cont.)

COAL LIQUEFACTION PLANTS PROPOSED UNDER ALTERNATIVE FUELS PRODUCTION ACT AND ENERGY SECURITY

Synthetic Product	Sponsor	Site	Process	Potential Production (BOE/day)	Start-up	Status
Gasoline	Clark Oil & Refining	St. Clair Co., IL	K-T; ICI; Mobil MTG	12,000	1988	Feasibility study awarded; loan and price guarantees requested from SFC.
Gasoline	W.R. Grace	Henderson, KY	Texaco; Mobil MTG	50,000	1987	DOE funded initial design; loan and price guarantees requested from SFC.
Gasoline	Hercules; W&WRR; United Coal	Montgomery Co., MD	-	23,000	-	Loan and price guarantee requested from SFC. Dropped.
Gasoline	A-C Valley Corp.	Venango Co., PA	K-T; ICI; Mobil MTG	10,000	1986	Loan guarantee requested from SFC under second solicitation.
Gasoline	Tennessee Synfuels Associates	Oak Ridge, TN	KBW; Pullman; Kellogg synthesis, Mobil MTG	10,000	1987	Loan and price guarantee requested from SFC under second solicitation.
Gasoline	Univ. of Tenn.	Jackson, TN	KBW; ICI; Mobil MTG	8,500	-	Applied for DOE feasibility study.
Gasoline	United Synfuels Corp.	Southwestern Va.	Mobil MTG	29,000	-	Applied for DOE feasibility study.
Syncrude (direct hydrogenation)	Breckinridge Energy Co.	Breckinridge Co., KY	H-Coal	25,000	1988	Loan guarantees requested from SFC; in Phase II evaluation.

Table 4 (cont.)

COAL LIQUEFACTION PLANTS PROPOSED UNDER ALTERNATIVE FUELS PRODUCTION ACT AND ENERGY SECURITY

Synthetic Product	Sponsor	Site	Process	Potential Production (BOE/day)	Start-up	Status
Gasoline	Amtur Inc. & Applied Energetics, Inc.	Green Co., AL.	GKT; ICI; MTA	10,000	1987	Loan and price guarantee requested from SFC under second solicitation.
Methanol	North Alabama Coal Gasification Consortium	Murphy Hill, AL.	GKT	25,000	1986	Loan guarantee requested from SFC under second solicitation.

The three generic approaches for producing liquids from coal - pyrolysis, direct hydrogenation, and indirect liquefaction - will be discussed in the following sections.

3.1 Pyrolysis

Pyrolysis can convert up to 25 percent of the coal to usable liquids. The process is basically hydrogenation with the hydrogen being provided by some of the coal molecules themselves or by entrained water molecules. When pyrolysis is practiced commercially in the manufacture of coke, coal tars and oils are produced as by-products.

When coal is pyrolyzed in the absence of oxygen, decomposition occurs. The hydrogen in the coal is redistributed to form a volatile fraction that has a hydrogen-to-carbon (H/C) ratio between 1.5 and 1.8. For comparison, a typical H/C ratio for crude oil is 1.5. If pyrolysis is carried out in the presence of hydrogen (to increase the product yield), the process is referred to as hydropyrolysis.

3.1.1 Pyrolysis Products

Pyrolysis produces light and heavy liquids, gases, and char in amounts that vary according to coal composition, and process conditions such as pressure, temperature, residence time, and composition of heating atmosphere. Typically, pyrolysis processes convert 50 percent or more of the coal to char. For this reason, pyrolysis processes appear best suited for multiproduct plants where the char can be gasified to produce hydrogen, fuel gas, or synthesis gas. The liquid products require further hydrogenation to reduce molecular weight and remove non-carbon atoms. This added refinement adds to the cost of the liquids, reducing the likelihood of their being used as fuels.

3.1.2 Pyrolysis Technologies

Table 5 presents a summary of the characteristics of the most advanced pyrolysis processes. Other pyrolysis processes that have been investigated but are not likely to contribute significantly to the production of coal liquids are shown in Table 6.

Table 5

PRIMARY PYROLYSIS LIQUEFACTION TECHNOLOGIES

Process	Development Status	Consumption (tons/day)	Type of Coal Used	Yield (bbl/ton)	Fuel Characteristics	Estimated Test in Prime Mover Candidates	Commercial Availability in U.S.
Lurgi-Ruhrgas	commercial[a]	1,600	lignite	1	50% char 18% oil[b]	none identified	-
Char-oil-energy-development (COED)	pilot plant; commercial design	36	bituminous	1.5	60% char 20% oil[b] 20% gas	none identified; boiler test	1986
Occidental pyrolysis	PDU[c]; commercial design	3 22,500	bituminous	1.7	57% char 35% oil[b] 8% gas	none identified	1986
Flash hydropyrolysis	PDU	24	bituminous	1.7	48% char 35% oil[b] 17% gas	none identified	early 1990's

[a] Operating in Yugoslavia.

[b] Hydrogen deficient.

[c] Process Development Unit

Table 6

SECONDARY PYROLYSIS LIQUEFACTION TECHNOLOGIES

Process	Development Status	Capacity (tons/day)	Type of Coal Used	Product State	Test in Prime Mover Candidates
Toscoal	Pilot plant	25	subbituminous; bituminous	80-90% char 5-10% oil 5-10% gas	none identified
Clean-Coke	PDU	0.5	bituminous	65% char 14% oil 15% gas 4% water	none identified
Coalcon	Pilot plant development suspended	18	noncaking	38% char 29% oil 10% gas 17% water	none identified
CSIRO	PDU	0.5	Australian	83% char 10% oil 3% gas 5% water	none identified

3.2 Direct Hydrogenation

Direct hydrogenation involves the addition of hydrogen to the coal molecular structure, either catalytically or by means of a solvent. The direct hydrogenation plants used in Germany during World War II produced 100,000 bbl/day of coal liquids, mostly aviation gasoline.

3.2.1 Products of Direct Hydrogenation

Distillate coal liquids produced by direct hydrogenation processes are lower in hydrogen but higher in nitrogen and oxygen than their petroleum-derived counterparts. Studies of commercial petroleum refining processes have shown that these coal-derived liquids can be upgraded practically to produce high-octane gasoline and distillate fuel oil. While diesel fuel and jet fuel also can be produced, the higher hydrogen consumption makes the processes for these end products less attractive.

3.2.2 Direct Hydrogenation Processes

Direct hydrogenation processes and their development statuses are listed in Table 7. Several direct hydrogenation processes under development are expected to be commercially ready in the early 1990's. These include SRC I and II (see Appendix, sections A.6 and A.7, respectively), EDS (see Appendix, section A.8), and H-Coal (see Appendix, section A.9). The two-stage liquefaction (TSL) process has the potential for higher liquid yields at lower hydrogen consumption than one-stage processes. In the first stage of TSL, dissolving of approximately 90 percent of the organic matter in the coal is followed by de-ashing. In the second stage, the intermediate product is upgraded in an expanded-bed catalytic hydrogenation unit resembling a commercial petroleum residual hydroprocessor. The TSL process is currently under development in a 10-gal/day process development unit (PDU). Full-scale testing is planned in conjunction with the SRC I demonstration plant.

The Federal Republic of Germany's Federal Ministry of Research Technology is developing a modern version of the one-stage Bergius process using a nonrecoverable, disposable catalyst, which trades off the higher catalytic activity of an optional catalyst for lower catalyst cost and process simplicity resulting from the elimination of a catalyst management system.

Table 7
DIRECT-HYDROGENATION COAL LIQUEFACTION TECHNOLOGIES

Process	Development Status	Capacity (tons/ day)	Type of Coal Used	Yield (gal/ ton)	Fuel Characteristics	Test in Prime Mover Candidates	Estimated Commercial Availability in U.S.
Bergius (two-stage)	commercial[a]; demonstration[b]	10,000 50	German brown, bituminous	-	syncrude upgraded to gasoline	- boiler test -	- 1988[c] -
Solvent Refined Coal I	PDU; pilot plant; demonstration plant design	6 50 6,000	all all all	-	low-S, low-ash, solid; anode-grade coke; distillate liquid (low-hydrogen)	- - -	-
Solvent Refined Coal II[d]	PDU; pilot plant; demonstration plant design	6 50 6,000	all all all	105	distillate liquid (naphtha, medium, and heavy)	boiler test; diesel test -	1988[c]
Exxon Donor Solvent	PDU; pilot plant	1 250	all	105-115	distillate liquid (naphtha, medium, and heavy)	boiler test -	1990
H-Coal	PDU; pilot plant; proposed	2.5 200[e] 10,000[f]	all	105-135	syncrude; distillate liquid; boiler fuel No. 6	boiler test - -	1988

See footnotes at end of table.

Table 7 (cont.)

DIRECT-HYDROGENATION COAL LIQUEFACTION TECHNOLOGIES

Process	Development Status	Capacity (tons/ day)	Type of Coal Used	Yield (gal/ ton)	Fuel Characteristics	Test in Prime Mover Candidates	Estimated Commercial Availability in U.S.
Two-Stage Liquefaction	PDU	0.1	all	-	distillate liquid	none identified	1988
Bergius (one-stage)	pilot plant under construction	200	all	-	distillate liquid	none identified	late 1980's
Liquid Solvent Extraction	PDU; pilot plant proposed	1 24	English coking	120	gasoline; distillate liquid	none identified	2000
Super-critical Extraction	PDU; pilot plant proposed	1 24	highly volatile, low-rank bituminous	110	(g)	none identified	2000

[a] In Germany, World War II.
[b] In United States.
[c] Assuming Federal support.
[d] Federal support for SRC II was withdrawn in July 1981.
[e] Syncrude.
[f] Loan guarantee requested from Synthetic Fuels Corporation.
[g] Unknown.

The process catalyst is an iron compound waste product of aluminum smelting. A 200-ton/day pilot plant under construction is scheduled for completion in 1981. Another plant of approximately 385 tons/day capacity is planned for operation in 1985.

The UK's National Coal Board is developing two processes: liquid solvent extraction (LSE) and supercritical extraction. Both processes are being tested in rate units of less than 1 ton/day. No reliable operating data are available.

3.2.3 Results of Further Treatment

The SRC II, EDS, and H-Coal process products can be upgraded to produce naphtha, middle distillates, and heavy distillates. Naphtha, after hydrotreatment using existing petroleum technology, is an excellent reformer feedstock producing a high-quality gasoline blending stock. Middle and heavy distillates can be combined as a No. 6 boiler fuel; or some fractions of the middle distillate can be used as a turbine fuel for use in low-NO_X-emission turbines. While specification diesel fuel and jet fuel can be produced, the higher hydrogen consumption makes these end products less competitive.

3.3 Indirect Liquefaction

The indirect liquefaction of coal involves the production of a synthesis gas composed of carbon monoxide (CO), hydrogen (H_2), hydrocarbons, and oxygen compounds produced by the gasification of coal; clean-up of the gas to remove sulfur; adjustment (shifting) of the hydrogen/carbon monoxide (H_2/CO) ratio of the gas to the desired level; and selective catalytic synthesis of the hydrocarbon and oxygen compounds into liquid fuels.

In this process, the technical characteristics of the gasifier govern the type of coal that can be used in the production of liquid products. The synthesis gas production and preparation account for 70 to 80 percent of the process cost. The properties of the synthesis gas, namely the H_2/CO ratio and methane (CH_4) content, have a pronounced influence on process efficiency because energy is required for shifting the H_2/CO ratio and reforming the CH_4. A large number of gasifiers can be used for this system. Table 8 summarizes the important characteristics of coal gasifiers most appropriate for use in indirect liquefaction and their stage of development.

Table 8
COAL GASIFICATION PROCESSES FOR INDIRECT LIQUEFACTION

Gasifier	Current Status	Yield/ (tons/ hour)	Pressure (atm)	Oxidant Air	Oxidant O_2	Feedstock Capability
Moving-Bed:						
Lurgi Dry Bottom	commercial	20-40	25	X	X	NAC[a]
Wellman-Galusha	commercial	2-10	1	X	X	NAC[a]
BBC Slagging Lurgi	commercial	10-15	25	-	X	all
Fluid-Bed:						
Winkler	commercial	25	1	X	X	NAC[a]
High-Temperature Winkler	developmental	1	10	X	X	NAC[a]
Westinghouse	developmental	0.6	10-16	X	X	all
U-Gas	developmental	0.3	3-23	X	X	all
Entrained:						
Koppers-Totzek (KT)	commercial	10-15	1	-	X	all
Shell-Koppers	developmental	6	30	-	X	all
Combustion Engineering (C-E)	developmental	5	1	X	-	all
Saarburg-Otto	developmental	11	25	X	-	all
Texaco	almost commercial	7-15	40	X	-	all
Mountain Fuel Resources	advanced concept	0.02	26	-	X	all
Rockwell Hydrogasification	advanced concept	0.25	70	-	X	all

[a] Nonagglomerating coal.

There are three major indirect liquefaction technologies: Fischer-Tropsch synthesis (see Appendix, section A.10), Mobil methanol-to-gasoline (MTG) synthesis (see Appendix, section A.11), and methanol synthesis (see Appendix, section A.12).

The Fischer-Tropsch process has been used since the 1930's. During World War II, Germany produced 10,000 bbl/day of high-quality diesel oil, low-grade gasoline, waxes, and oxygenated products by this process. A modified Fischer-Tropsch process has been used in a commercial facility by the South

African Coal, Oil, and Gas Company (SASOL) since 1955. SASOL I produces approximately 5,000 bbl/day of transportation fuel, while SASOL II and III, scheduled to start operations in 1982 and 1984, respectively, will bring the total capacity of the Union of South Africa up to approximately 100,000 bbl/day. The entrained-bed reactor used in SASOL I, II, and III operates at 25.5 atm at 315° to 330°C. The reactor gives a lighter product distribution, with about 35 percent of the Btu output as naphtha and 26 percent of the Btu output as C_1 and C_2 hydrocarbon gases.

Downstream processing of the raw Fischer-Tropsch products involves fractionation, hydrotreating, catalytic reforming, and other petroleum refining steps. Some of these steps produce light gases. If these gases are combined with the light gases and methane produced in a Lurgi gasifier, a light gas yield of 60 percent of the total Btu output is achieved by the total system. The thermal efficiency of such a combination plant would be in the range of 50 to 55 percent. Because the gases cannot serve as a transportation fuel, they must either be sold as coproducts or reformed into synthesis gas for recycling. The low overall efficiency (40 to 45 percent) of the all-liquid-product Fischer-Tropsch plants results from this need to reform the methane produced from both the gasifier and the synthesis reactors.

A principal problem of the Fischer-Tropsch process is the relatively high-pressure steam requirements for coal gasification and shift-conversion steps for the production of a synthesis gas with an H_2/CO ratio of 2 to 2.5 necessary for the reactor. To reduce the steam requirements and improve the efficiency of the overall process, an effort is underway to use a synthesis gas with a low H_2/CO ratio. This work centers on the Kolbel synthesis reactor, which operated in the Rheinpreussen, Germany, from 1938 to 1953.

3.4 Estimated Costs for Producing Coal-Derived Liquids

A review of the recent cost estimates for producing coal-derived liquids was conducted for this study. The estimated cost of derived diesel fuel ranged from approximately \$0.75/gal to \$1.25/gal (1980 dollars) as compared to the average railroad diesel fuel cost of \$0.81/gal in 1980. The range of the estimates is shown in Figure 2. The data include costs for processing and upgrading synthetic fuels to a specification diesel fuel in the Fischer-Tropsch and direct hydrogenation cases. Cost estimates for gasoline and methanol are also presented. All costs in Figure 2 have been normalized to a constant energy density of 138,000 Btu/gal, equivalent to No. 2 diesel fuel.

3.4.1 Future Estimates and Costs

The most significant conclusion regarding the cost data is that the costs of coal-derived liquids are likely to remain greater than products refined from natural petroleum for some time. Using the median cost estimate, coal-derived diesel fuels currently cost at least 25 percent more than petroleum-based fuels. Given that synthetic fuel plants would take 6 to 10 years to design and construct, the price of coal-derived fuel relative to petroleum-based diesel fuel can reasonably be expected to be high for perhaps 10 to 15 years. However, as experience is gained with constructing and operating coal-based synthetic fuel plants, a gradual decrease in the relative price of coal-derived fuel to petroleum-based diesel fuel can be expected in the long term.

3.4.2 Cost Estimate Uncertainty

Cost estimation for synfuel processes is made especially complex by the fact that the processes used make several products. This is shown in Table 9, which shows the product slates for several of the previously discussed coal liquefaction processes.

Consider the difficulties encountered in computing costs of the products when several products are being produced simultaneously. The fact that the costs of the plant must be allocated over several products can lead to significant marketing errors. For example, if the fraction of the costs allocated to product A is too low, the calculations may suggest that large profits can be realized on sales of product A. In addition, with the same assumptions, the fraction of the costs allocated to product B will perhaps be too high, implying large losses for sales of product B. This may be a distortion of the real market. Disastrous results are avoided by using a cost allocation method that relates calculated product costs for the entire product slate to the total market value of each of the various products.

Because the market value of fuel products on a cost per Btu basis varies widely, any attempt to rank processes on this basis will be quite

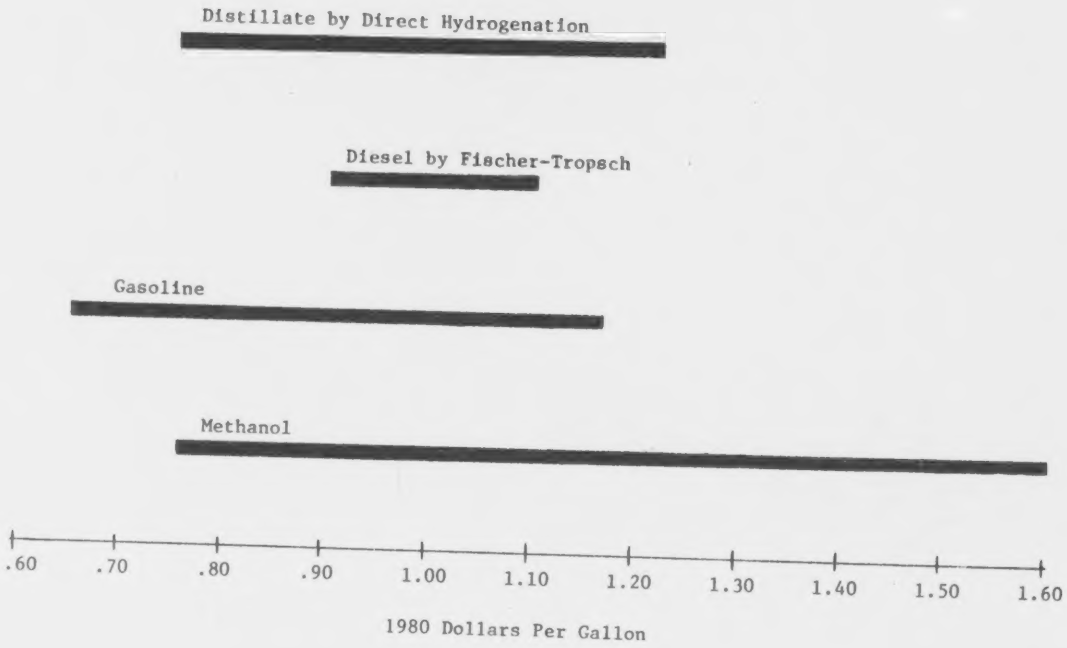

Figure 2. Estimated Cost Ranges for Several Coal-Derived Liquid Products

Table 9

PRODUCTS SUMMARY BASIS: PLANT FEED RATE OF 25,000 TONS/DAY DRY COAL[a,b,c]

Process	Product	Yield (amount/day)
SRC-II	LPG	5,500 bbl
	naphtha	10,700 bbl
	fuel oil	43,300 bbl
	gas	23.1 MMscf
EDS	propane	3,270 bbl
	butane	3,500 bbl
	naphtha	19,900 bbl
	fuel oil	28,700 bbl
	C_2 gas	41.9 MMscf
H-Coal (fuel oil)	naphtha	18,200 bbl
	fuel oil	42,200 bbl
	gas	19.7 MMscf
H-Coal (syncrude)	naphtha	31,900 bbl
	fuel oil	24,300 bbl
	gas	56.3 MMscf
Fischer-Tropsch	gasoline	18,200 bbl
	LPG	18,800 bbl
	No. 2 oil	1,200 bbl
	fuel oil	2,000 bbl
	medium Btu gas	90.7 MMscf
	C_2 gas	37.2 MMscf
Methanol-to-gasoline	premium gasoline	52,700 bbl
	LPG	7,300 bbl
Methanol	methyl fuel	113,400 bbl
	methanol	8,400 bbl

[a] Products have been adjusted for source coal high heat value (HHV) to a common basis of 11,200 Btu/lb (dry).

[b] In the table, fuel oil means low-sulfur boiler fuel comparable to No. 6 oil.

[c] Cases shown as MMscf (million standard cubic feet) are determined at 20°C, 1 atm pressure.

misleading. In addition, product slates differ greatly from process to process. Only a few (highly sophisticated) cost estimates in the literature attempt to assess future relative values of each of the products for the different synfuel processes.

The labor to develop reliable industrial estimates may cost as much as 5 to 10 percent of the actual cost of the proposed project, a not inconsiderable sum. For example, if it is assumed that construction costs of a 50,000-bbl/day coal-derived liquids plant would be between $2 and $2.5 billion, the estimate might cost $100 million. However, the result of the estimate may be worthwhile if it indicates overall profitability of the project or prevents further financial waste.

3.4.3 Price Differential Between Petroleum Products and Coal Products

In 1970, most of the synthetic fuel experts seriously thought that only minor increases in the cost of petroleum resources would make synthetic fuel processes economically competitive. Over 10 years have passed, and the price of petroleum has increased more than 10-fold, yet synthetic fuel processes are still not economically competitive. The fact that synthetic fuel prices have remained always higher than the competition must be explained.

Two phenomena seem to be important in explaining the apparently continuing price gap between synthetic and petroleum fuel. The first is the pervasive general inflation. There have been significant increases in the costs of coal and coal processing; inflation is not confined to petroleum and its derivatives.

The second phenomenon involves the improvements in synthetic fuel processes. The original designs for processing facilities use simple concepts not thoroughly investigated. As research and development continue, process complexity evolves and adequate designs become more costly than the original ones. Implementation of these processes thereby grows in cost even more rapidly than the inflation rate.

3.5 Environmental Pollution and Safety Issues

A number of environmental, health, and safety questions must be addressed before commercial use of coal-derived liquids can be achieved. These questions involve production, transportation, handling, storage, and use of the products. Recent results from laboratory studies have shown that the potential for toxicity and carcinogenicity varies greatly depending on the product and the amount and kind of refining it receives.

3.5.1 Health Hazards

Before a fuel can be commercially marketed, the producer has to file a premanufacturing notification (PMN) with the Environmental Protection Agency (EPA), as required under the Toxic Substances Control Act (TSCA). Synthetic fuels have to undergo strict toxic substances review. Supporting data from detailed chemical analyses and preliminary toxicological screenings have to be supplied. For materials showing potential for carcinogenicity, extensive testing programs must be carried out. Joint EPA-DOE working groups are currently attempting to establish functional TSCA policies that will provide adequate public health and safety protection, while still allowing the synthetic fuels industry to proceed.

Liquid fuel refined from coal is expected to be no more toxic than fuel refined from petroleum. Although analyses have shown that intermediate products can have toxic and carcinogenic properties, proven upgrading methods can be used to eliminate sulfur and nitrogen from the fuels, reducing the polynuclear aromatics to a level comparable to similar petroleum-derived products. Properly executed plant health and safety measures, as practiced in the petroleum (and chemical) industries, should be adequate to protect workers in the synthetic fuel processing and upgrading facilities.

The coal liquid products of primary interest to the railroad industry, namely naphthas, diesel fuel, and fuel oil fractions, are expected to be required to go through PMN review. Table 10 presents a summary of PMN requirements for Fischer-Tropsch products. Naphtha fractions from the Fischer-Tropsch process probably will not exhibit significant potential hazard

Table 10

SUMMARY OF PMN REQUIREMENTS AND POTENTIAL PROBLEMS FOR FISCHER-TROPSCH PRODUCTS

Fraction	Composition	Probable PMN Review Requirements	Problem Areas
SNG	Primarily methane.	Should be exempt.	-
Butanes	Primarily butane; some butylenes.	If not exempt, chemical analyses to determine exact composition.	Butane and butylenes are not new substances; however, the mixture may be so judged.
Naphthas	Primarily straight-chain monounsaturated and saturated hyrocarbons.	Chemical analyses and toxicological tests.	-
Diesel fuel oil	Primarily straight-chain hydrocarbons.	Chemical analyses and toxicological tests, the extent of the latter depending on the results of screening tests.	-
Fuel oil	Higher molecular weight components.	Chemical analyses and extensive toxicological tests.	Likely to exhibit toxicity. This fraction may not occur in U.S. processes.

to health or the environment. Tests on samples of similar products from petroleum, oil shale, and liquefaction of coal have shown little evidence of mutagenicity or carcinogenicity. Nevertheless, to gain approval under TSCA the PMN for the naphthas has to include enough chemical analyses and toxicological tests to prove they will not be harmful in use.

Direct coal liquefaction preserves much of the aromatic character of the coal, increasing the probable incorporation of potential carcinogens in the diesel fuel fraction. The diesel fuel fraction from a Fischer-Tropsch process however, is not expected to exhibit as much mutagenic or carcinogenic potential as similar fractions derived from direct coal liquefaction. The Fischer-Tropsch process breaks up the aromatic compounds in the gasification stage; the subsequent liquefaction produces primarily straight chain aliphatic hydrocarbons, reducing the probability of carcinogenic hazard. However, the health risk of the Fischer-Tropsch diesel fuel can only be judged when its components are completely known and testing has been performed on them.

3.5.2 Safety Aspects of Using Methanol

EPA has stated that methanol is exempt from PMN review. Currently, transportation of methanol is regulated by the Department of Transportation (DOT). Because methanol is classified as a flammable liquid, the DOT has issued safety specifications for its shipment and storage in drums, tank cars, etc., and has described handling procedures to prevent fires. Methanol is one of the largest bulk chemicals in commerce today. The statutes and regulations in place are necessary to effectively protect against major spills and fires.

Except in the DOT labeling requirements, the toxicity of methanol does not come under regulation. Methanol is not on the EPA list of hazardous substances for which discharges must be reported. Officials at the EPA agree that the subject of methanol spills will have to be studied before widespread use of methanol is permitted. An environmental impact statement dealing with the problem is expected to be prepared long before there is widespread use of methanol as a fuel.

Methanol spills are more readily cleaned up with far less danger of fire than gasoline spills. Flushing with water disperses the methanol completely.

Upon flowing into any body of water, methanol is soon diluted to an inconsequential concentration. EPA officials feel that dangers to the environment from use of methanol will be localized and transient. Toxicity to humans is of the same order as that involved in the handling of gasoline.

One further problem to be considered would be the occupational exposure to methanol vapors by locomotive refueling personnel. For example, the Occupational Safety and Health Administration (OSHA) benzene vapor standard of 10 ppm is met by keeping the benzene content of gasoline below 0.1 percent. The OSHA standard for methanol vapor is 200 ppm, 20 times the benzene standard. Experiments have to be conducted to see whether locomotive refueling personnel pumping 100 percent methanol for 8 hr are exposed to vapors in excess of the OSHA standard. Methanol, somewhat less volatile than benzene, has a lower boiling point. The vapor concentration from 100 percent methanol is expected to be more than 20 times that of 0.1 percent benzene. It may therefore be necessary to use special vapor recovery systems or personal protection equipment to protect workers under these conditions.

PART III. COAL PRODUCTS AS RAILROAD LOCOMOTIVE FUEL

Because of the wide variety of fuel products that can be made from coal, virtually any locomotive engine could be fueled by coal products. Some engines could use more than one, but most engines could probably not use more than two of the coal products reviewed in this report.

Use of a coal product would not necessarily be the least expensive alternative for life cycle costs even if that product is initially cheaper than its equivalent petroleum product. Without providing life cycle economic comparisons, this report does discuss some of the issues involved, such as fuel cost, fuel storage and delivery system cost, locomotive maintenance, locomotive reliability, and environmental constraints.

1. Prime Movers

The following engine types are discussed in this report:

- Diesel-electric engines
- Gas turbine engines
- Fuel Cell engines
- Stirling cycle engines
- Rankine steam engines

Table 11 shows the applicability of various currently available (or soon to be available) coal products for each of these engines.

1.1 Diesel-Electric Engines

The acceptability of a coal-derived product as a primary fuel or as an extender for diesel fuels depends on a number of factors, including compatibility with existing diesel engines; engine performance; ease of distribution, storage, and handling; environmental health and safety factors; and costs.

1.1.1 Fuel Properties, Specifications, and Performance

To evaluate the compatibility of coal-derived fuels with existing diesel-electric engine fuel systems, it is necessary to define the critical

Table 11
APPLICABILITY OF COAL-BASED FUELS[a] TO RAILROAD PRIME MOVERS

Prime Mover	Solid-Lump or Pulverized	Carbon Black	Coal Oil or Water Liquid	Fischer-Tropsch Distillate	Methanol	H-Coal
Diesel-electric	not usable	possibly usable	possibly usable	acceptable	possibly usable	acceptable
Gas turbine	possibly usable[b]	possibly usable	possibly usable	acceptable	acceptable	acceptable
Fuel cell	not usable	not usable	not usable	acceptable	acceptable	acceptable
Stirling cycle	probably usable	probably usable	acceptable	acceptable	acceptable	acceptable
Rankine steam	acceptable	acceptable	acceptable	acceptable	acceptable	acceptable

[a] All coal-based fuels listed could be made acceptable as fuels for remote power plants for electrified railroads.

[b] Closed-cycle or pressurized, fluidized bed.

fuel performance parameters. Performance features and physical properties most directly related to these features are summarized as follows:

Performance feature	Fuel property
Safety in handling	Flash point
Pumpability at low temperatures	Viscosity; pour or cloud point
Ignitability	Cetane number
Clean lines in burning	Volatility
Atomizability	Viscosity
Engine wear, emissions	Sulfur, ash, and other impurities
Fuel degradation	Storage stability
Freedom from all suspended matter	Suspended sediment
Power output per unit amount of fuel	Heating value

Relationships between fuel characteristics and the performance of the engine and its accessories summarized by Exxon are presented in Table 12.

Table 12

RELATIONSHIP OF FUEL PROPERTIES TO ENGINE PERFORMANCE CHARACTERISTICS

Fuel Property	Power Output	Fuel Consumption	Starting	Warmup	Combustion Chamber Deposits	Power Assembly Wear	Injection System Deposits and Wear	Pumpability and Filterability	Exhaust Smoke and Odor	Lubricant and Lubrication
Volatility (boiling range)	Low volatility may reduce power due to power atomization. High volatility may result in inadequate droplet penetration or cause vapor lock, also reducing power.	Low or high volatility may result in high fuel consumption due to improper mixing of fuel and air.	Too high a temperature for 10% evaporated may adversely affect starting.	Fast warmup is, as well as Cetane No. (C.N.), directly related to the front end volatility characteristics of the fuel The lower the temperature for the 10-50% evaporated, the faster the warmup.	Too high a boiling range or too high a 90% point and end point (E.P.) may cause incomplete combustion and excessive combustion chamber deposits.	Carbon deposits coupled with incompletely burned fuel may promote ring and liner wear.	No direct effect except for possible wear due to vapor lock.	No direct effect.	More volatile fuels tend to reduce exhaust smoke during idle and acceleration. Related to C.N.	Incomplete combustion due to too low volatility may cause lube oil dilution.
Flash Point	Related to handling hazards. Low flash point may indicate contamination with gasoline or naphtha.									
Ignition quality	No effect if C.N. is high enough for fuel ignition under light load and low temperature operation. Excessively high C.N. may require readjustment of injection timing.	Same effect as on power output.	Directly affected by by C.N. The higher the C.N., the better the starting.	Direct effect. Coupled with high front-end volatility, the higher the C.N. the faster the warmup.	Combustion chamber deposits are usually fluffier and and more readily purged from engines operated on high C.N. paraffinic fuels.	No direct effect except as C.N. affects completeness of combustion.	No effect.	No direct effect. High C.N. fuels may have high cloud and pour points.	Direct effect. Increase in C.N. usually reduces exhaust smoke and odor at idle and light load. Related to volatility.	No direct effect except as C.N. affects completeness of combustion.

Table 12 (cont.)

RELATIONSHIP OF FUEL PROPERTIES TO ENGINE PERFORMANCE CHARACTERISTICS

Fuel Property	Power Output	Fuel Consumption	Starting	Warmup	Combustion Chamber Deposits	Power Assembly Wear	Injection System Deposits and Wear	Pumpability and Filterability	Exhaust Smoke and Odor	Lubricant and Lubrication
Viscosity	Too low viscosity may cause reduced power output due to pump leakage and also may cause injector wear if combined with poor filtration. Droplet penetration affected by viscosity.	Same as for power output	No direct effect except as related to volatility.	No direct effect except as related to volatility.	No direct effect except as related to volatility.	No direct effect except as related to volatility.	Too low viscosity combined with poor filtration may accelerate barrel and plunger wear.	Too high viscosity may may cause fuel filter collapse, or cause cavitation at low temperatures.	No direct effect except as related to volatility.	Related to volatility High viscosity fuels may cause incomplete combustion due to poor penetration or mixing of droplets with air.
Cloud point	No effect.	No effect.	High cloud fuel may plug filter and prevent fuel from reaching combustion chamber.	No effect.	No effect.	No effect.	High cloud fuel may plug filter, thus preventing fuel from reaching injection system and causing wear.	High cloud fuel may cause filter plugging.	No effect.	No effect.
Pour point	No effect.	No effect.	High pour may plug filter and prevent fuel from reaching combustion chamber.	No effect.	No effect.	No effect.	High pour fuel may plug filter, thus preventing fuel from reaching injection system and causing wear.	High pour fuel may cause filter plugging.	No effect.	No effect.

Table 12 (cont.)

RELATIONSHIP OF FUEL PROPERTIES TO ENGINE PERFORMANCE CHARACTERISTICS

Fuel Property	Power Output	Fuel Consumption	Starting	Warmup	Combustion Chamber Deposits	Power Assembly Wear	Injection System Deposits and Wear	Pumpability and Filterability	Exhaust Smoke and Odor	Lubricant and Lubrication
Sulfur content	Possible increase in combustion chamber deposits and wear may eventually reduce power output.	Same effect as on power output.	No effect.	No effect.	High sulfur fuel may cause high temperature deposit formation may also be related to lube oil properties and oil drain intervals.	High sulfur fuel may cause increased ring and liner wear, particularly at light bonds.	High sulfur fuel may cause injection system deposits and wear.	No direct effect. High sulfur content may be related to fuel instability, a cause of fuel filter plugging.	High sulfur fuel may adversely affect odor and lachrymation.	High sulfur fuel may adversely affect lubricant performance.
Corrosion	No effect.	No effect.	No effect.	No effect.	No direct effect. May increase fuel gum due to attack on brass or copper.	No effect.	May cause corrosion of brass or copper parts in the system	May cause corrosion of filter assemblies containing brass or copper. High gum formation accelerated by brass or copper parts may cause plugging.	No effect.	May have adverse effect on lubrication due to gum formation.
Stability	No direct effect.	No direct effect.	No effect.	No effect.	Instability may result in deposit formation.	No direct effect.	May cause lacquering of pump and injector parts.	May cause filter plugging.	No direct effect.	May affect lubrication adversely due to gum formation.
Carbon Residue	May cause injector tip deposits, disturbing atomization.	Same effect as with power output.	No effect.	No effect.	May increase deposits if compression ratio is too high.	May cause increased wear.	May cause injector tip deposits and seizure of injection system parts.	May cause filter plugging.	May cause increased smoking.	May increase burden on the lube oil.

Table 12 (cont.)

RELATIONSHIP OF FUEL PROPERTIES TO ENGINE PERFORMANCE CHARACTERISTICS

Fuel Property	Power Output	Fuel Consumption	Starting	Warmup	Combustion Chamber Deposits	Power Assembly Wear	Injection System Deposits and Wear	Pumpability and Filterability	Exhaust Smoke and Odor	Lubricant and Lubrication
Ash	May cause wear which will indirectly affect power output.	Same as for power output.	No effect.	No effect.	Excessive ash may increase deposit level and affect nature of deposits.	Excessive ash may aggravate wear.	High ash may cause abrasion of injector system parts.	No direct affect.	No direct effect.	No direct effect.
Water and sediment	No effect.	No effect.	No effect.	No effect.	No direct effect.	May increase wear if material passes into combustion chamber.	May increase deposits and wear.	May cause filter plugging.	No direct effect.	No direct effect.
Gravity	Low gravity (API) fuels may increase power output due to higher heating value per unit volume.	Fuel economy may improve for given throttle setting for low gravity (API) fuels due to higher heat content per unit volume.	No direct effect. Related to C.N. and volatility.	No direct effect. Related to C.N. and volatility.	No direct effect. Related to C.N. and volatility.	No direct effect.	No direct effect.	No direct effect but related to volatility and viscosity.	No direct effect but related to C.N. and volatility.	No direct effect but related to C.N. volatility, and viscosity.

Source: Compiled by Exxon from published information.

Under the broad definition of diesel fuel, there exist many possible combinations of the various characteristics of volatility, ignition quality, viscosity, gravity, stability, and other properties. To characterize the resulting diesel fuels, thereby establishing a frame of reference, various classifications are used, including particularly ANSI/ASTM D975-78, Standard Specification for Diesel Fuel Oils. This classification covers three grades of diesel fuel oils, Nos. 1-D, 2-D, and 4-D, as shown in Table 13. Sets of certain minimum requirements necessary to insure reasonable diesel operations are listed. The standards do not represent complete sets of quality specifications for these fuel oils; only a means for their classification. Grade No. 2-D is a distillate fuel, the type most commonly used in railroad engines. Grade No. 4-D represents a class of more viscous distillates or a blend of distillates with residual fuel oils applicable for use in low- and medium-speed engines.

Most of the railroads use a good grade of all distillate ASTM No. 2 diesel oil meeting the requirements shown in Table 13. These ASTM requirements have been supplemented by specific recommendations made by major locomotive manufacturers, as presented in Table 14.

Cetane number, one of the most important fuel performance parameters governs ignition. A satisfactory diesel fuel must self-ignite readily and quickly upon injection into the hot compressed air produced by the compression stroke. As cetane number is reduced, ignition delay increases, resulting in difficulties in starting when external temperature and pressure conditions are unfavorable. Furthermore, as the cetane number decreases, the ignition delays increase engine knock, thus decreasing engine durability. Conversely, if the engine is supplied with a fuel having a high cetane number, performance may be improved, particularly in terms of the ability to start under cold conditions or at high altitudes.

Fuel viscosity affects the design of the fuel system. The use of high-viscosity fuels is limited by restrictions imposed by fuel filters and lines. These restrictions are reduced by increasing fuel supply pressure, redesigning of fuel filters, and increasing fuel line diameters.

Table 13

DETAILED REQUIREMENTS FOR DIESEL FUEL OILS FROM ASTM D975-78[a]

Grade of Diesel Fuel Oil[b]	Flash Point (°C) (min)	Cloud Point (°C) (max)	Water and Sediment (vol%) (max)	Carbon Residue On, 10% Residium (%) (max)	Ash (wt%) (max)	Distillate Temperatures °C 90% Point (min)	(max)	Viscosity Kinematic, cs[c] at 40°C (min)	(max)	Saybolt, SUS at 100°F (min)	(max)	Sulfur[d] (wt%) (max)	Copper Strip Corrosion (max)	Cetane Number[e] (min)
No. 1-D	38	(f)	0.05	0.15	0.01	-	288	1.3	2.4	-	34.4	0.50	No. 3	40[g]
No. 2-D	52	(f)	0.05	0.35	0.01	282[h]	338	1.9	4.1	32.6	40.1	0.50	No. 3	40[g]
No. 4-D	55	(f)	0.05	-	0.10	-	-	5.5	24.0	45.0	125.0	2.0	-	30[g]

[a] To meet special operating conditions, modifications of individual limiting requirements may be agreed upon between purchaser, seller, and manufacturer.

[b] No. 1-D is a volatile distillate for engines in service requiring frequent speed and load changes. No. 2-D is a distillate fuel oil of lower volatility for engines in industrial and heavy mobile service. No. 4-D is a fuel oil for low- and medium-speed engines.

[c] 1 cs = 1 mm^2/s.

[d] In countries outside the U.S.A., other sulfur limits may apply.

[e] Where cetane number by Method D613 is not available, ASTM Method D976, Calculated Cetane Index of Distillate Fuels[2], may be used as an approximation. Where there is disagreement, method D613 shall be the referee method.

[f] It is unrealistic to specify low-temperature properties that will ensure satisfactory operation on a broad basis. Satisfactory operation should be achieved in most cases if the cloud pint (or wax appearance point) is specified at 6°C above the tenth percentile minimum ambient temperature for the area in which the fuel will be used. The tenth percentile minimum ambient temperatures for the U.S. are shown in Appendix X2 of the source document. This guidance is of a general nature; some equipment designs, use flow improver additives, fuel properties, and/or operations may allow higher or require lower cloud point fuels. Appropriate low temperature operability properties should be agreed on between the fuel supplier and purchaser for the intended use and expected ambient temperatures.

[g] Low-atmospheric temperatures as well as engine operation at high altitudes may require use of fuels with higher cetane ratings.

[h] When cloud point less than -12°C (10°F) is specified, the minimum viscosity shall be 1.7 cs (or mm^2/s) and the 90% point shall be waived.

Table 14

FUEL RECOMMENDATIONS - U.S. LOCOMOTIVE DIESEL ENGINES

		Manufacturers		
Inspections	ASTM Designation	General Motors Corp. Electromotive Division	Class A	Class B[a]
Cetane number[b], (min)	D-613	40	45	40
90% point, °F (max)	D-86	650	650	675
Final boiling point, °F (max)	D-86	700	700	-
Distillate recovery, % (min)	D-86	99.0	-	-
Total sulfur, % (max)	D-129	0.5[c]	0.75	1.0
Corrosive sulfur, 3 hr @ 122°F	D-130 (Mod)	No. 2 or better	No. 3 max	No. 3 max
Carbon residue, 10% bottoms (max)	D-189	0.15	0.15	0.35
Water and sediment, % (max)	D-96	0.05	0.05	0.10
Cloud point, °F (max)	D-97	(d)	-	-
Pour point[e], °F (max)	D-97	(d)	(f)	(f)
Flash point, °F (min)	D-93	150	125 or legal	125 or legal
Viscosity @ 100°F, kinematic, cs	D-445	1.8-5.8	1.8-5.8	1.3-5.8
Viscosity @ 100°F, SUS	D-88	32-45	32-45	32-45
Organic chlorides, ppm (max)	UOP No.395	20	-	-
Filtration cleanliness test, mg/1 (max)	(g)	1.3[h]	-	-
Ash, % by wt. (max)	D-482	0.02	0.02	0.02

[a] Use of Class B fuels will require additional maintenance and more careful control and selection of lubricating oil.

[b] Low atmospheric temperature as well as engine operation at high altitudes may require use of fuels with higher cetane ratings.

[c] The maximum total sulfur content has been set at 0.50% or legal. Fuels containing larger amounts of sulfur can be used but will increase engine wear and maintenance.

[d] Prevailing ambient temperature.

[e] For normal summer operations, a pour point of 25°F maximum is satisfactory. For winter conditions, the oil should have a pour point not less that 10°F lower than the expected temperatures.

[f] For cold weather operation, the pour point should be specified 10°F below the ambient temperature at which the engine is to be operated, except where fuel oil heating facilities are provided.

[g] ASTM 1962 D-2 Report, Appendix X, page 35.

[h] Ash residue on 0.80 micron filter.

Source: Compiled by ER&E from published information.

The diesel engines used in railroad applications are tolerant of metallic impurities in the fuel up to an ash content of 0.1 percent by mass, though special features such as water cooled valves are needed to withstand aggressive attack from vanadium compounds (a frequent constituent of residual petroleum fuels). Primary requirements of the diesel engine are (1) the fuel shall pass the close tolerances of the fuel handling equipment (pump and injectors) without causing rapid wear and (2) the fuel shall be well atomized as it passes from the injector into the combustion chamber. With "dirty" fuels the clean-up is accomplished usually by centrifuging enroute to the engine; viscosity control at the injectors is obtained by preheating. Both of these methods may be considered state of the art.

1.1.2 Performance Characteristics of Coal-Derived Liquids

The composition of the fuels from coal liquefaction processes is highly variable, depending on the processes, process conditions, and the degree of upgrading feasible.

1.1.2.1 Products From Direct Pyrolysis

Pyrolysis produces a heavy, aromatic liquid high in heteroatom concentration and containing char that has to be removed before combustion. This product, suitable for boiler fuels, requires substantial upgrading for use in internal combustion engines. In general, pyrolysis products are unsuitable for use in diesel engines or other internal combustion engines, but could be used in externally fired engines such as steam engines, Stirling engines, and closed-cycle prime movers.

1.1.2.2 Products From Direct Hydrogenation

Direct hydrogenation produces several different qualities of raw coal liquid products. All of these differ from petroleum crude oil and distillates. They are generally high in aromatic, condensed-ring and heteroatom (nitrogen, oxygen, and sulfur) concentrations. In Table 15 the ranges of values presented for the more significant properties of H-Coal, EDS, and SRC II distillates reflect differences in process operating conditions

Table 15
DIRECT HYDROGENATION LIQUID PROPERTIES

Property	H-Coal Syncrude[a]	EDS[b]	SRC II Distillate[c]
Cetane number	-	-	16
Gravity, °API	6.6-19	4.6-27.4	12.3-18.6
Viscosity @ 100°F, cs	2.5-4.4	1.4	0.1-3.8
Flash point, °F	170	-	168-178
Sulfur, wt %	0.16-0.22	0.4	0.26-3.4
Boiling range, °F	282-570	340-534	304-820
Heating value, Btu/lb	17,300	18,090-18,650	13,100-17,200
Pour point, °F	5-(-100)	-	(-56)-(-80)
Aromatics, %	-	-	91
Ash, wt %	-	-	0.0023-0.004

[a] H-Coal Liquid from Illinois No. 6 Coal, Literature Survey of Properties of Synfuel Derived from Coal, Lewis Research Laboratories, NASA, February 1980.

[b] Synthetic Fuels Technologies: Cost, Product Quality and Environmental Data, Energy Resources Co., Inc.

[c] Southwest Research Institute Sample No. PAMCO 1723, March 9, 1980.

[d] Converting SRC II Process Product to Transportation Fuels, Chevron Research Co., August 6, 1979.

(such as temperature, pressure, and solvent recycle), coal composition, and fuel analysis techniques.

To be used as transportation fuels the distillate fractions must be processed to produce near-specification fuels. Coal-derived naphtha fractions, particularly after two-stage reforming, produce excellent high-octane gasoline blend stocks. Refining the direct hydrogenation products to less aromatic turbine or diesel fuel is more difficult. In general, products of this quality, particularly if blended with petroleum-derived turbine or diesel fuel, should cause few problems in current engines.

Research has been conducted on upgrading coal-derived liquids to transportation fuels. Table 16 presents the results of a test conducted by Chevron Research Co. on upgrading to diesel fuel H-Coal synthetic crude made from Illinois No. 6 coal. A very satisfactory diesel fuel was made from the H-Coal liquid; however, the upgrading adds significantly to the cost of the product. For example, upgrading the H-Coal product to diesel fuel requires a hydrogen consumption of about 2200 scf/bbl corresponding to a cost of $8/bbl to $12/bbl ($0.19 to $0.29 of a total cost of distillate ranging from $0.72/gal to $1.24/gal).

Table 16
DIESEL FUEL FROM H-COAL

Property	Diesel Fuel Specification ASTM D 975-78 No. 1-D	No. 2-D	Properties of the 250°F Product from Severely Hydrofined Illinois H-Coal Oil
Cetane number	40	40	42.5
Cloud point	varies	varies	50
Sulfur, wt %	0.5	0.5	0.001
Flash point (Pensky-Marten), °F	100	100	116
Ash, wt %	0.01	0.01	0.002
Distillation 90%, °F	550	540-640	524
Viscosity @ 40°C, cs	1.3-2.4	1.9-4.1	1.678
Viscosity @ 100°F, SUS	34.4	32.6-50.1	32.1
Corrosion, copper strip	No. 3	No. 3	No. 1
Aromatics	-	-	2.7

Source: Assessment of Long-Term Research Needs from Coal Liquefaction Technologies, Fossil Energy Research Working Group, March 1980.

1.1.2.3 Products From Indirect Liquefaction

Indirect liquefaction either produces a slate of liquid products (e.g., the Fischer-Tropsch process) or only a single liquid product (e.g., the Mobil MTG and the methanol processes). Indirect routes through gasification and Fischer-Tropsch synthesis or methanol synthesis and MTG conversion also produce very different products.

1.1.2.4 Products from Fischer-Tropsch Process

Fischer-Tropsch synthesis products, highly paraffinic, may contain appreciable amounts of chemically combined oxygen, but they are essentially free of nitrogen and sulfur. These products present no particular refining problems other than those associated with high paraffinicity, i.e., high pour points, high cloud points, and low octane number. The product slate produced by the Fischer-Tropsch process depends on the reactor used. Table 17 presents the product mix for both the Arge and Synthol reactors. The naphthas are a mixture of straight-chain monounsaturated and saturated hydrocarbons free of sulfur and nitrogen. The products in the automotive gasoline distillate range have a heating value of 20,430 to 20,815 Btu/lb. The naphthas may be hydrogenated to produce turbine fuel.

Table 17
TYPICAL SASOL PRODUCT MIX FROM FISCHER-TROPSCH PROCESS
(percent)

Product	Arge Fixed-Bed	Synthanol Entrained-Bed
Liquefied petroleum gas	5.6	7.7
Naphthas (C_5-C_{11})	33.4	72.3
Medium oils (diesel)	16.6	3.4
Waxy oils	10.3	3.0
Medium wax	11.8	-
Hard wax	18.0	-
Alcohols and ketones	4.3	12.6
Organic acids	trace	1.0

Source: Assessment of Technology for the Liquefaction of Coal, National Academy of Sciences, Washington, D.C., December 1977.

The diesel fuel product of the Fischer-Tropsch process, composed primarily of straight-chain hydrocarbons free of sulfur and nitrogen, has a heating value of approximately 20,450 Btu/lb. The properties of this diesel fuel (see Table 18), particularly a cetane number above 60, qualify it as acceptable. The fuel oil product (see Table 19) is a waxy sulfur-free product with a high pour point (150°F). Its heating value of 19,850 Btu/lb is adequate for use as boiler or turbine fuel.

1.1.2.5 Products From the Mobil MTG Process

The Mobil MTG process uses a shape selection zeolite catalyst to convert methanol to aromatic high-octane motor fuel. The properties of the fuel are almost identical to those of fuel derived from petroleum. There are no data on the properties of the diesel or jet fuel produced by varying the residence time and catalyst construction in the fluidized-bed process.

Table 18

FISCHER-TROPSCH DIESEL OIL PRODUCT PROPERTIES

Property	Grade[a]	Test
Gravity, °API	57	ASTM D287
ASTM distillation:		ASTM D86
initial boiling point	301 °F	
10%	327 °F	
30%	351 °F	
50%	372 °F	
70%	421 °F	
90%	539 °F	
end point	637 °F	
percent recovered	98%	
Viscosity at 100°F, cs	1.4	ASTM D445
Flash point, °F, Pensky-Marten	100	ASTM D93
Pour point	Plus 10	ASTM D97
Aniline point, °F	175	ASTM D611
Oxygen content, wt %	0.5 (max)	
Sulfur, wt %	nil	ASTM D129
Mercaptan sulfur	nil	ASTM D1323 or D1219
Neutralization number (mg KOH per g)	0.1	ASTM D611
Corrosion, copper strip:		
at 150°F	No. 1	ASTM D130
at 210°F	No. 1	
Ash, wt %	less than 0.01	ASTM D482
IP smoke point, mm	25	(IP designation 57)
Engine cetane number	60 plus	ASTM D613
Kieldahl nitrogen, ppm	nil	ASTM D322

[a] ASTM D975 specification for No. 1-D fuel.

1.1.2.6 Products from Methanol Processes

The third fuel produced by indirect liquefaction is methanol. Even though there are a large number of methanol synthesis processes they all produce the same product.

1.1.3 Compatibility of Coal Liquids with Railroad Diesels

The ability to substitute coal-derived liquids directly for petroleum-derived diesel oil in the railroad diesel depends on many factors. From the

Table 19
FISCHER-TROPSCH FUEL OIL PRODUCT PROPERTIES

Property	Grade	Test
Higher Heating Value, Btu/lb	19,855	ASTM D2382
Gravity, °API	41	ASTM D287
ASTM distillation:		
initial boiling point	572 °F	ASTM D86
5%	642 °F	
10%	665 °F	
30%	715 °F	
50%		759 °F
50%	811 °F	
90%	873 °F	
95%	886 °F *	
end point	885 °F	
Viscosity at 100°F, SUS	155	ASTM D88
Flash point, °F, Pensky-Marten	200	ASTM D93
Pour point, °F	150	ASTM D97
Color, Saybolt	dark	ASTM D1500
Oxygen, wt % (max)	0.5	
Sulfur	nil	ASTM D129

previous discussion, Fischer-Tropsch diesel oil can definitely be substituted directly for petroleum-derived diesel oil. The only potential problem is the pour point, which may be somewhat high (above 10°F) for cold weather conditions; however, the high cetane number greater than (60) enables the blending of the Fischer-Tropsch diesel oil with a better pouring, less costly product (the result could have cetane number below 40). Extensive laboratory testing by Southwest Research Institute (SwRI) has shown that a diesel engine can operate satisfactorily at a limiting cetane of 37 before a significant increase in engine knock is observed. Limited knocking was observed in the 32-37 cetane range. A proper mix of the Fischer-Tropsch diesel oil and petroleum-derived or synthetic fuel is thus expected to offer a significant reduction in cost over the use of 100 percent Fischer-Tropsch diesel fuel; however, operational testing has yet to be performed.

The direct-hydrogenation coal liquid can be upgraded to produce a fuel substitutable directly for petroleum-derived diesel fuel. As shown in

Table 15, diesel fuel from the H-Coal process equals or exceeds the ASTM specification. If the railroad diesel could use off-specification diesel fuel (as the SwRI tests indicated), the severity of hydrofining the direct liquids would be reduced, with cost savings. For example, the hydrogen consumption in the upgrading of H-Coal to a satisfactory diesel fuel could be reduced by 25 percent, a savings of $2.50/bbl would be achieved.

Another approach for using coal-derived fuels in diesel engines involves engine modification. SwRI simulated coal-derived fuels and methanol in an engine converted to operate in a dual-fuel configuration. The tests were conducted on a two-cylinder version of the Electro-Motive Division (EMD) model 567 B engine, which has a bore of 8.5 inches, a stroke of 10.0 inches, an engine displacement of 567 cubic inches per cylinder, and a maximum governed speed of 835 rpm. The dual-fuel conversion involved the installation of two engine-driven single-cylinder injector pumps at the end of the generator and a small-diameter, pencil-type injector in the pressure relief port in each cylinder. The auxiliary pumps and injectors were used to inject pilot diesel fuel. The main fuel (methanol or simulated coal-derived fuel) was introduced through the EMD unit injectors. Limited engine performance optimization was conducted. The conclusions derived from these tests by SwRI were the following:

- "A simulated coal-derived fuel can be consumed when the engine is operated in the dual-fuel mode. Pilot diesel fuel can initiate combustion and overcome the low cetane number of simulated fuel. Without the pilot, severe knock occurs.

- Thermal efficiencies and power output were below baseline levels at all tested dual fuel conditions and slight knocking was present. It is believed that improvements in injection parameters will overcome these problems."

SwRI also conducted dual-fuel tests with SRC II. SwRI reported that good performance was obtained at all notch positions tested. At notches 4 and 8, thermal efficiencies comparable to baseline diesel fuel were obtained but not without slight knocking. SwRI discovered an unusual technique for dual fueling the engines in the laboratory. In dual-fueling operations, a small amount of pilot diesel fuel is injected prior to the injection of the SRC II charge. Compression ignition of the diesel fuel ignites the SRC II. The pilot is normally injected 10 to 20 degrees before the main charge. SwRI found that advancing the injection of the pilot charge allowed more time for the diesel fuel to burn before the SRC II is injected, helping reduce the knock produced by the main charge. However, if the pilot fuel is advanced beyond a certain point, "misfire" occurs because the fuel disperses and evaporates, preventing compression ignition. SwRI found in this situation that combustion should start shortly after the start of the SRC II injection. Given sufficient quantities of pilot diesel fuel, the resulting operation is virtually knock-free and thermal efficiency is equal to or improved over baseline diesel fuel operation. At notch 8, 5 to 10 percent (on a Btu basis) pilot fuel is needed. At lower notch settings, more pilot fuel is required. For example, 40 percent pilot is required at notch 2. In summary, the results of the SwRI SRC II dual-fuel test were promising.

The Department of Energy's Bartlesville Energy Technology Center is sponsoring a number of diesel engine tests using shale oil and SRC II. General Electric Company (GE) has also conducted tests using a blend of 30percent SRC II and 70 percent diesel fuel in an unmodified GE locomotive engine.

With respect to dual-fuel operation with methanol the following conclusions were reported by SwRI:

- "Knock-free operation can be achieved with methanol, assisted by pilot diesel fuel injection, at power outputs and thermal efficiencies which were sometimes higher than for No. 2 diesel fuel ---." "Severe knock and misfiring occur without pilot injection."
- "The methanol tests were restricted to notch 6 or below. The available unit injectors were not capable of supplying sufficient volume of methanol for full power methanol operation above this position. Oversized injectors must be developed before notch 7 and 8 methanol operation is successful." This is because of the low heating value of methanol (58,000 Btu/gal) as compared to No. 2 diesel oil (130,000 Btu/gal).
- "Injection equipment lubrication is a problem when handling methanol. A suitable lubrication system must be developed and proven before the alcohol can be acceptable for field use."

1.1.4 Solid Coal-Fired Diesel Engine

The coal-fired diesel engine dates back to independent theoretical activities and occasional unsuccessful experiments conducted in the 1880's. In 1892, Rudolph Diesel was issued a patent on a self-ignition internal combustion engine that used liquid as well as solid fuel. However, his experiments with coal proved unsuccessful; discouraged, Diesel ceased further work with solid fuels. Rudolph Pawlikowski, one of Diesel's coworkers, made significant advances in the technology of coal-fired diesels between 1911 and 1940. Pawlikowski solved many of the basic problems concerning fuel feed, control systems, seals, and lubricants. He demonstrated successfully the fuel-flexibility of his engine on fuels ranging from flour to hard coal.

Between 1915 and 1945, five companies in Germany conducted independent development programs in coal-fired diesel engines; approximately 20 coal-fired diesel engines reached commercial use. The state of technology of coal-fired medium-speed diesels is summarized as follows:

- Fuel Feeding and Control. Several techniques have been developed that should allow satisfactory operation of a low speed coal-fired diesel. Two basically different types of fuel injection have been developed and tested: direct injection of air-fluidized coal dust from the prechamber into the engine cylinder by compressed air from an external air compressor and self-injection of fluidized coal dust from the prechamber into the cylinder by means of pressure generated in the prechamber by precombustion of part of the fuel. Both techniques, while having some problems, should be operable. An alternative in fuel feeding would be to feed the coal dust in compacted form as solid rods to the engine inlet, thus easing fuel handling, reducing transportation costs, and easing the explosive hazard.

- Wear, Attrition, and Erosion. In the early coal-fired engines, excess wear of essential engine parts was the most serious detriment to long-term operation. Wear is caused by the amplification of the normal friction between surfaces by abrasive particles such as mineral ash and unburned carbon and erosion of components exposed to flow of high-speed gas containing abrasive particles. New wear-resistant materials developed for cylinder liners and piston rings give improved life; however, life is not as long as that attained in an oil-fired diesel. Another possibility is to develop technology that will allow the ultracleaning of coal to remove most of the ash and other abrasive material. Research on technologies for ultracleaning of coal is currently being sponsored by DOE.

- Efficiency. Coal-fired diesel efficiency ranges between 26 and 35 percent, somewhat lower than for the oil-fired diesel. The efficiency includes consideration of power losses for driving auxiliary equipment and friction losses in the engine. The friction can be exceedingly high when hard abrasive fuel particles such as ashes and unburned carbon are caught by the lubricant on the cylinder walls.

In summary, major advances in materials, coal cleaning, fuel feeding, and control technology are necessary for coal-fired diesel engines to become economically competitive with oil-fired diesel engines.

1.2 Gas Turbine Engines

The use of a gas turbine in a locomotive was initially attempted in Germany in the early 1930's; however, early attempts did not result in a competitive prime mover. The Union Pacific Railroad placed 55 gas turbine locomotives ranging in size from 4,500 to 10,000 hp into service between 1952 and 1961. Not able to compete economically with the diesel, they were retired from service in 1969.

The gas turbine has appeal as a railroad prime mover because it is mechanically simpler than the diesel, more compact, lighter, and less costly per horsepower; however, the gas turbine lags behind the diesel in thermal efficiency, which falls off very rapidly at part load. Furthermore, the gas turbine has very high fuel consumption at idle, approximately 30 percent of the full load usage, compared to about 3 percent for the diesel. The part-load efficiency of the gas turbine can be significantly increased by use of the regenerative cycle, in which some of the heat in the exhaust gas is transferred to the compressed gas between the compressor and combustion chamber. This reduces the amount of fuel needed for combustion. Research is underway to increase the firing temperature of industrial and utility gas turbines from approximately 2,000°F to approximately 2,600°F. This will improve the efficiency to about 38 percent.

The gas turbine can use coal-derived liquid fuels. For example, the products of direct hydrogenation can be upgraded to produce a suitable turbine fuel. Table 20 illustrates the characteristics of turbine fuel produced from SRC II and H-Coal. However, to produce this fuel, it is necessary to severely hydrotreat the product from the process. The cost of upgrading is approximately $12/bbl.

Table 20
TURBINE FUEL FROM COAL-DERIVED LIQUIDS

Property	Jet A Specification	H-Coal Turbine Fuel[a]	SRC-II Turbine Fuel[b]
Gravity, °API	37-51	36.3	34-36
Smoke point, °F	20 (min)	23	20-21
Aromatics, vol %	20 (max)	2.7	10-16
Existent gum	7 (max)	incomplete	0
Copper strip corrosion (2 hr at 212°F)	No. 1	No. 1	No. 1A
End point, °F	572	589	570
Flash point, °F	100 (max)	108	100-138

[a] Assessment of Long-Term Research Needs for Coal Liquefaction Technologies, Fossil Energy Research Working Group, University of California, March 1980.

[b] Converting SRC-II Process Products to Transportation Fuels, Chevron Research Company, August 1979.

Tests have been conducted on a utility-sized gas turbine using methanol. Operations were satisfactory; emissions were below those normally associated with petroleum-derived turbine fuel. Furthermore, it is also expected that a satisfactory turbine fuel can be produced from the Fischer-Tropsch process; however, operating characteristics are unknown.

1.2.1 Open-Cycle Gas Turbine Using Solid Coal

Development of a coal-burning gas turbine started before World War II in Europe. This turbine was to be used for stationary applications. Significant problems with coal feed, combustion, turbine blade erosion, and fuel use rates (efficiency) were encountered.

1.2.1.1 Early Efforts

In 1954, the Locomotive Development Committee of Bituminous Coal Research, Incorporated, initiated the development of a coal-fired gas turbine. The goal was to develop a technically advanced coal-fired prime mover for locomotive traction that could meet the challenge of the diesel-electric locomotive. At the time, the diesel was about to displace the steam locomotive, thereby eliminating the large railroad coal market. A 400-hour test was conducted in 1958 on a 3,500-hp Allis-Chalmers open-cycle gas turbine. Severe blade erosion occurred, especially at the roots of the rotor blades. This work led to the in-service testing of a 5,000-hp coal-fired gas turbine by the Union Pacific Railroad, starting in 1962 and terminating in 1964. The system consisted of a coal pulverizer, coal feed, combustor, ash separater, and gas turbine. The pulverizer, coal feed, and combustor appeared to work satisfactorily; however, the ash separater and other parts of the gas cleaning system did not perform as required. Consequently, the turbine blades soon wore out.

In a research program in Australia, a modified Ruston and Hornsby gas turbine operated on pulverized coal. Blade life exceeding 20,000 hours was expected to be achievable if the gas stream was cleaned of all particulates above 20 microns and the turbine blades were redesigned. Turbine manufacturers in the U.S. and Europe are also conducting R & D programs on coal-fired turbine designs and blade materials for reducing erosion and alkali metal corrosion. Further, a test program using a coal-water mixture fuel for a gas turbine is being planned by DOE. This test should be complete in 1983.

Since this early work on a coal-burning gas turbine, much research has been directed at design of the critical components of the system, the combustor, gas cleanup, and gas turbine blades. Most of this research has focused on eventual application to utility electric power generation.

1.2.1.2 Pressurized-Fluidized-Bed Combustion

The United States, United Kingdom, and Federal Republic of Germany have conducted an intensive joint R & D program in pressurized-fluidized-bed combustion (PFBC). In the PFBC system, either air or steam heated in the combustor is used to provide power. The hot off-gas (at 1,600°F) from the combustor is then cleaned of particulates and expanded through a gas turbine to produce additional power. This system has a projected efficiency of 38 to 40 percent in electric power generation applications, compared to 33 percent for a conventional pulverized coal-fired plant with a flue gas desulfurization system. The PFBC combustion has been shown to be technically feasible. An

85-megawatt thermal combustor will be demonstrated in 1982 at Grimethoupe, United Kingdom. Furthermore, DOE is conducting an extensive hot gas clean up R & D program directed at reducing the particulate loading in the pressurized, fluidized bed or gasifier gas streams to a level suitable for expanding through a gas turbine without undue erosion of the turbine blades.

While the coal-fired gas turbine using the PFBC appears to be technically feasible for industrial and utility applications, its application as a source of power for locomotives has not been investigated.

1.2.2 Closed-Cycle Gas Turbine Using Solid Coal

Another option for using coal directly, the closed-cycle gas turbine has had limited use in power plants in Europe. Five power plants have been operating in Germany, each with far more than 100,000 hours.

The closed-cycle gas turbine system has five major components: the combustor, heat exchanger, gas turbine, recuperator, and cooler. The primary difference between the open-cycle gas turbine and the closed-cycle gas turbine is the ducting of the turbine exhaust back to the compressor inlet. The working fluid in the closed-cycle system can be air, helium, argon, krypton, or a number of other gases.

The closed-cycle gas turbine exhibits excellent part-load cycle thermal efficiencies of about 36 to 49 percent with current-technology heat exchangers. The development of ceramic heat exchangers would permit turbine inlet temperatures to be raised to between 2,200° and 2,300°F, resulting in a cycle thermal efficiency of over 40 percent.

While the efficiencies of the closed-cycle system are attractive, a number of developmental problems exist, including (1) development of small high-temperature heat exchangers, (2) development of an efficient coal or coal mixture combustion, (3) use of an inexpensive safe working fluid, and (4) development of a small, efficient recuperator.

Garrett AiResearch Incorporated has considered the application of a 4,700-hp closed-cycle gas turbine unit in a locomotive. This application would be attractive if the technical problems are overcome through asignificant R & D effort. No demonstrated application of the closed-cycle gas turbine in a locomotive is known.

1.3 Stirling Engine

The Stirling engine is an external combustion, closed-cycle power plant that uses gas, usually hydrogen or helium, as an internal working fluid. The working gas is heated by an external source. The use of an external combustor in the Stirling engine allows the engine to operate on a variety of fuels; however, the external combustor makes the three heat exchangers the most important aspect of Stirling engine design. These units are the heater head, regenerator, and cooler. The heater head transfers heat from the external combustor to the engine working gas. The cooler transfers heat from the working gas to the external coolant. The regenerator serves a dual purpose, both storing and releasing heat within the cycle. The Stirling engine thus requires larger heat exchanger capacity than an internal combustion engine, increasing its weight and cost.

The Stirling engine, believed to be less sensitive to fuel characteristics than internal combustion engines, therefore should be operable on Fischer-Tropsch liquids; moderately upgraded SRC II, EDS, and H-Coal liquids; and methanol. Using coal or a coal mixture would be more difficult because of the potential for fouling the heater head surfaces. Philips Research Laboratories in the Netherlands has operated a small research engine from heat generated by coal. The use of fluidized-bed combustion to provide the necessary heat pipe for heat transfer and sulfur capture can be achieved within the combustor without the need for additional SO_x control; however, heat pipes or a heat transfer loop require substantial development, and the fluidized-bed combustor must be demonstrated and tested in a mobile environment.

The first known investigation for applying the Stirling engine to locomotives was conducted by EMD during the 1960's under a licensing agreement with Philips Research Laboratories. Different versions of a four-cylinder engine were tested using a variable phase angle control system. Details of this work have not been published in the open literature; however, some bearing and vibration problems were reported. A management decision was made in 1970 by EMD to terminate the licensing agreement.

In summary, the efficiency of the Stirling is high and its potential multifuel capability would be an advantage, particularly if direct coal or coal mixtures could be used; however, the need for large heat transfer surfaces would increase the size and weight of the locomotive. Furthermore, significant development activities would have to be pursued to prevent fouling of heat transfer loops by ash from the coal combustion.

1.4 Fuel Cell Engines

The fuel cell is an excellent device for generating electricity by energy conversion. The technology was first applied in the space program in the 1960's. The fuel cell engine converts chemical energy directly to dc electrical energy without the limitations of the Carnot cycle. The fuel cell has significant advantages, including high efficiencies (over 50%), negligible air emissions, no noise, and modular design.

The typical fuel cell system has two integrated components, the fuel processor and the fuel cell stack. The fuel processor converts the fuel to a hydrogen-rich gas through a catalytic reaction. Several different types of fuel cells being developed by a number of industrial concerns are generally classified on the basis of the type of electrolytes used. These are (1) acid, (2) alkaline, (3) molten salt, and (4) solid oxide. The only fuel cell that could be considered for locomotive application in the relatively near term (early 1990's) is the phosphoric acid system presently being developed under government sponsorship. The phosphoric acid fuel cell operating at approximately 400°F can convert hydrogen to dc electricity with an overall efficiency of over 40 percent. The phosphoric acid fuel cell is currently being tested in stationary applications, the largest being a 4.8-megawatt unit being demonstrated by Consolidated Edison in New York.

Advanced fuel cells, such as the molten carbonate, are expected to offer efficiencies over 50 percent; however, much R & D must be done before these advanced systems are ready for commercial application.

The fuel cell uses hydrogen and oxygen taken from its fuel. Naphtha and methanol appear to be the best sources of these materials because of their low sulfur content, a requirement to avoid poisoning the cell. Methanol would require the simpler on-board fuel processor; the methanol steam reformer also operates below 610°F, while the naphtha reformer requires 1,725°F. Also, very little shift conversion is required for methanol. Although the processor for converting methanol to a hydrogen-rich gas is more efficient, smaller, and operates at a lower temperature than the naphtha reformer, the space saved is offset by the increased volume needed for on-board fuel storage because the energy density of methanol is approximately one-half that of naphtha.

A key problem with the application of fuel cells to locomotive use is the power density, that is, the amount of power that can be generated for a given volume and weight. The current diesel has a weight-to-power ratio of 20 lb/kw and a volumetric ratio of about 0.4 ft^3/kw. The phosphoric acid fuel cell operating on methanol could reach 30 lb/kw and 1 ft^3/kw for a 10-kw size. Larger and more advanced fuel cells are expected to have better power densities. For example, the potassium hydroxide (KOH) electrolyte fuel cell designed by Exxon has a weight density of 6.3 lb/kw and a volumetric density of 0.44 ft^3/kw. In addition to the power density problem, R & D activities by industry and Government are being directed at reducing platinum loadings, improving cell cooling, improving electrode resistance to corrosion, eliminating acid leakage and deflation, and developing manufacturing techniques.

In summary, the fuel cell could provide an efficient means for powering a locomotive with coal-derived liquids; however, extensive R & D remains to be done. Assuming success, the phosphoric acid fuel cell will probably be ready for locomotive application by the late 1980's. Advanced fuel cells, such as the molten carbonate fuel cell, will probably achieve technical readiness by the mid-1990's.

1.5 Steam Engines

Steam served American railroads for over 125 years as the prime means of locomotive power. In 1951, over 21,000 steam locomotives were in service, whereas today there are only 12. The diesel-electric locomotive was responsible for this demise, which took place in the 15-year period between 1945 and 1960. Several factors contributed to this rapid displacement:

- The diesel-electric was more thermally efficient (32 percent versus less than 10 percent).

- The diesel-electric, simpler and more flexible in its operation, thus reduced costs (it required fewer operating personnel and fewer facilities such as round-houses, water tanks, and coal-loading facilities).
- The diesel-electric reduced maintenance costs, not only for maintenance of the locomotive, but also of rail and road beds, through the more even application of power to the drivers.
- The diesel-electric was much cleaner environmentally than the coal-fired steam locomotive.
- Multiple-unit control allowed longer trains with a single locomotive crew.

Steam, however, still has some advantages that justify reconsideration as an option for the future. The most significant advantage is that steam can be raised through direct use of coal. The technology of utility and industrial steam raising using coal has advanced since 1960. Efficiency from coal pile to steam header of 38 to 40 percent is attainable today; however, environmental controls reduce these values to 33 to 36 percent.

1.5.1 The ACE 3000 Steam Locomotive

The most recent work on an advanced steam locomotive has been the conceptual design of a 3,000-hp coal-fired locomotive by American Coal Enterprises, Incorporated. The ACE 3000 unit consists of a 4-8-2 locomotive and a service module that contains coal packs, ash packs, and steam condensor. The steam cycle of the ACE 3000 results in three claimed improvements over the conventional steam locomotive: (1) increased fuel efficiency (2) low water use, and (3) smooth rail-locomotive interaction. The ACE 3000 uses proven technology components from prior era steam locomotives and present era boiler control and diesel electric locomotives. However, the full locomotive system has yet to be demonstrated.

The heat-raising unit is a two-stage combustor. In the first stage, warm underflow air passes through the coal bed to gasify the coal. The second stage involves the injection of overflow air at low velocity, completing the combustion process. This process is claimed to have several advantages, namely, reduced fly ash and soot, reduced fouling of the fire tube heat transfer surfaces, and reduction in flue gas clean-up problems. The bed operates at 2,000°F to meet the ash agglomeration requirements. Coal is fed to the boiler by means of a stoker grate by a conveyor from the coal pack located in the service module. The flue gas is cleaned of fly ash and other particulate matter by multiple cyclones. Boiler bottom ash and fly ash are conveyed to a closed

5-ton-capacity ash pack in the service module. The latter can be cleaned out during servicing.

The 300-psi steam passes through a superheater to a four-cylinder compound engine driving four pairs of 54-inch wheels. The piston valves, double ported on low-pressure cylinders, are driven by Walschaertz gears with cut-off controlled by microprocessor outputs determined by power requirements and adhesion conditions. The steam powers a forced-draft flue gas exhaust turbine, which allows a steady stream of flue gas emissions. The exhaust steam then goes to a condensor aboard the locomotive, where direct contact with the boiler feed water returns it to a liquid state. The hot liquid is then passed through a large heat exchanger in the service module, driving its air-circulating fans. This condensing system allows for a reduction of water use from approximately 1 gal to approximately 0.3 gal of water per pound of coal.

Using coal with a sulfur content of 1.5 percent, the ACE 3000 emissions are expected to be 1.8 lb/MBtu of SO_x, less than 0.41 lb/MBtu of NO_x, and 0.1 lb/MBtu of particulates.

A summary comparison of the ACE 3000 and a 3,000-hp diesel-electric locomotive is as follows:

Characteristics	ACE 3000	Diesel-Electric (EMD)
Locomotive weight (lb)	650,000	256,000
Fuel weight (lb)	66,000[a]	30,000[b]
Water weight (lb)	83,000[c]	2,000[d]
Total weight (lb)	799,000	288,000
Length (ft)	112	59
Width (ft)	10	10
Height (ft)	15	15
Capital cost ($M)	1.25	0.8
Efficiency (%)	15-18	32
Bidirectional operations	yes	yes

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[a] 33 tons of coal.
[b] 3,600 gal of diesel fuel.
[c] 10,000 gal of water.
[d] 254 gal of water.

The operability of the ACE 3000 steam locomotive appears comparable with that of the existing diesel-electric locomotive. The major areas of concern are coal and ash handling, distribution, and storage; treated water requirements; condensing and equivalent dynamic braking capabilities; microprocessor control of traction and boiler; and locomotive size and weight.

1.5.2 Problems of Transition to Coal-Fired Steam Locomotives

The current railroad system provides for the storage and handling of approximately 4.1 billion gallons of diesel fuel each year. Storage tanks, pipelines, and refueling stations are in place at approximately 2,000 railroad yards throughout the nation. A transition to 100 percent total coal usage would mean the storage and handling of approximately 41 million tons of coal per year, assuming a coal heat content of 13,800 Btu/lb and an efficiency of 15 percent for a coal-fired steam locomotive. In addition, over 3.5 million tons of ash, based on coal with 9 percent ash, must be disposed of according to EPA regulations.

If, for example, coal handling and storage were required at each refueling location, the following would be required: a coal unloading facility, short-term (1-day) and long-term (30-day) storage areas, coal crushing and sizing equipment; thaw sheds (in areas where freezing is possible), conveyors, train loading facilities, fire protection, water runoff control, and other facilities. The ash waste disposal system would consist of ash storage bins or silos, ash loading facilities, and an ash disposal land fill. The cost of these facilities would be substantial. An independent estimate made during this study showed that the capital cost for a coal preparation and handling facility of 20 locomotive capacity would be approximately $4 million. This estimate was based on equipment and installation cost data for a similar industrial coal preparation and handling system. If a centralized, large-scale facility located at a mine were used to prepare the coal and load the ACE 3000 coal packs, the preparation cost is estimated to be approximately $6/ton.

The ACE 3000 uses treated boiler feed water to reduce the maintenance costs associated with boiler tube scaling. The capital cost of a 100,000-gal/day water treatment facility would be about $200,000. This facility would be of sufficient size to service 10 locomotives per day. In addition, it is estimated that water treatment chemical costs of approximately $0.03/gal and other costs of $0.03/gal would result in a total treated watercost of approximately $0.06/gal. The water treatment costs are highly dependent on the initial quality of the water.

Ash handling and disposal represent another cost unique to the steam locomotive. The ACE 3000 would use ash packs to store the ash from the boiler. These packs would be off-loaded during refueling. Ash disposal costs would be approximately $40/ton, depending on transportation costs and land fill availability.

One of the factors that led to the displacement of the steam locomotive by the diesel-electric locomotive was the reduction in maintenance cost. Recent studies assessing maintenance costs associated with the modern steam locomotive range from about 67 percent less to 20 percent more than the corresponding diesel engine cost. American Coal Enterprises, Incorporated, states that the ACE 3000 locomotive should have maintenance costs equal to the diesel-electric locomotive. Firm data on maintenance cost, downtime, mean time between failures, and other maintenance-related data will not be available until a modern steam locomotive is demonstrated in railroad service.

Although no modern steam locomotive such as the ACE 3000 has been demonstrated as a full system, the modern steam locomotive is within the state of technology. The technical and engineering problems of integrating known components into a complete operating locomotive system are not thought to be insurmountable.

The majority of the steam locomotives of the past, as well as the ACE 3000, use a reciprocating expander to drive the wheels; however, several locomotives use a steam turbine as an expander.

The steam turbine has been used with great success in utility and industrial applications; however, its use in mobile sources has been primariy limited to marine applications. Steam turbines for small applications (such as locomotives) are not well developed. The efficiency is low (50% to 60%) and drops rapidly at part load. There is not much incentive to develop small steam turbines with efficiencies high enough to warrant use in a locomotive.

In summary, the modern coal-fired steam locomotive can use coal directly as a fuel; however, the major obstacles to the direct coal-fired locomotive would be the technology adoption and infrastructure necessary for its operation and maintenance. Installation of new facilities for coal refueling, water treatment and ash handling would be a significant effort. Furthermore, modification of current maintenance facilities and retraining of maintenance and operating personnel would be major activities.

2. Railroad Electrification

Railroad electrification represents a potential application of indirect coal usage to power locomotives. At the turn of the century, the U.S. led the world in railroad electrification. As late as the early 1930's, the U.S. owned 20 percent of the world's total electrified lines; now less than 1 percent of the railroad trackage in this country is electrified. Outside the North American continent, electrification is rapidly becoming the standard way to expand high-volume, mainline railroads. Many of the major industrial countries such as France, West Germany, Japan, and the Soviet Union have electrified at least 25 percent of their railroad systems.

There are approximately 1,000 route miles of electrified trackage in the U.S. today. The most recent electrification projects, excluding rapid-transit systems, consist of coal-hauling railroads: the Muskinghum Electric Line (15 route miles) at Zanesville, Ohio; the Black Mesa and Lake Powell Railroad (78 route miles); and two in eastern Texas operated by Texas Utilities Service.

The Black Mesa and Lake Powell electrified system, the first commercial-frequency electric railroad operation in the country, operates at 50 kV, 60 Hz. It is a fully automated, two-train operation, with unmanned electric locomotives controlled by remote signalling and communications systems. Passive transponders are mounted between the rails at specific intervals. The locomotives used in this system were the first in the U.S. to be built with thyristor propulsion control. This system has been operating successfully for over 15 years. By using a 50-kV, instead of a 25-kV, catenary, the total number of power substations required for this railroad was reduced from three to one.

2.1 Advantages and Disadvantages of Railroad Electrification

Many studies performed by individual railroad companies, the Federal Railroad Administration, and others in the private sector have examined the advantages, disadvantages, and uncertainties of electrification. Some of the advantages of electrification are as follows:

- Reduction in the consumption of petroleum products in the railroad industry. Assuming that the busiest 10 percent of the nation's railroad trackage was electrified, savings could exceed 2 billion gallons of diesel fuel a year, one-half of the total fuel consumption.
- Reduction in locomotive maintenance cost. Maintenance costs of electric locomotives would be approximately one-third of those experienced with diesel electric locomotives.
- Reduction in number of locomotives. Fewer electric locomotives would be required for electrified routes because of higher availability and less maintenance. Furthermore, the higher available power per axle for electric locomotives would allow fewer units per train to produce the same performance as diesels at all speed ranges.
- Reduction in inventory of materials, including petroleum fuel, lubricating oil, and replacement parts for the diesel engine.
- Reduction in environmental problems (e.g., air pollution).

Some of the disadvantages of electrification are as follows:

- Enormous capital outlay and generally low rate of return on investment.
- Loss in flexibility of locomotive fleet operations. Electric locomotives cannot operate on nonelectrified tracks. A dual-mode diesel electric locomotive equipped with current pick up and a transformer to operate as a straight electric locomotive in electrified territory is a proven concept. It would allow a railroad to speed up its use of the electrification investment and it would improve locomotive and train crew utilization. However, it would increase the unit capital cost of locomotives and increase the weight.
- Interference problems with existing signalling and communications systems from the high-voltage wiring. Such problems may necessitate retrofit of these existing systems at a significant cost.
- Electric power dispatchers are required to control train operations to avoid peak power charges from the utilities and overloads of substations.

- Overall route downtime due to train derailments is likely to increase because of the additional precautions and time required to repair and restore service on electrified lines.

2.2 Economic Issues

The principal obstacles to railroad electrification involve the resolution of economic as opposed to technical considerations. The major financial and economic issues are the following:

- The capital investment required for railroad electrification would create a long-term obligation that would affect the credit standing and ability of railroad companies to raise capital for other necessary railroad improvements. Estimates of the cost to electrify 10 percent of the total U.S. trackage range between $6 and $10 billion. The industry is currently spending approximately $4 billion per year to maintain and upgrade the existing railroad system.
- Savings in diesel fuel derived from electrification of part of the railroad system may be offset by increases in the price of future electric power.

In addition to the cost of the electrification system, the cost of electric locomotives must be considered, although in some cases, this would not require substantial additional investment because such locomotives would substitute for diesel-electric locomotives that the railroad would have to purchase anyway. Additional costs of structural changes in track conditions such as bridge and tunnel clearances and new investment in electric power facilities could be quite substantial.

If railroad electrification is installed on the 20,000 miles of high-density trackage that carries roughly 50 percent of the nation's traffic, the railroads would create an estimated annual demand for about 3 billion watt-hr. Potential traffic growth on the same rail lines could increase this annual demand to levels in excess of 30 billion kilowatt-hr. These levels of demand of electric power imposed by railroad electrification, however, represent less than 1 percent of the national peak demand.

REFERENCES

The ACE 3000: Maintenance and Payback, John T. Harding, American Coal Enterprises, Incorporated, April 23, 1981.

Advances in Synthetic Fuels Technology: Progress in USA/DOE Programs, G. Fumich; H. Perry, Fifth International Conference on Coal Research, Dusseldorf, Federal Republic of Germany, September 1980.

Alternative Energy Sources for Non-Highway Transportation, Exxon Research and Engineering Company.

Alternative Fuels for Medium Speed Diesel Engines (AFFMSDE), Project First Research Phase Final Report Off-Specification Diesel Fuels, Simulated Coal-derived Fuel and Methanol; Southwest Research Institute.

Aspects of Commercializing Coal-Derived Methanol Fuels in the United States 1985 to 2000, Volume I Market Evaluation, Assistant Secretary for Resource Applications, U.S. Department of Energy, March 1980.

Assessment of Long-Term Research Needs for Coal Liquefaction Technologies (FERWG-II), University of California, March 1980.

Assessment of Technology for the Liquefaction of Coal, National Academy of Sciences, December 1979.

Catalytic Hydrogenation of Coal Derived Liquids, Department of Chemical Engineering, Montana State University, August 1980.

The Coal Burning Gas Turbine Project, Report of the Interdepartmental Gas Turbine Steering Committee, Department of Minerals and Energy, Australian Government Printing Service, 1973.

Coal Conversion Comparisons, The Energy Societies Commission on Energy Inc. (Draft), July 1979.

Coal Liquefaction; Current Federal Programs and Technologies, Draft, MITRE Corporation, 1979.

Coal Liquefaction Direct versus Indirect - Making a Choice, Dale Simbruk, Ronald Dickenson, James Moll, Synthetic Fuels Associates, Oil and Gas Journal, May 4, 1981.

Coal Synfuel Facility Survey, National Coal Association, August 1980.

Cogeneration Technology in Europe, R. Harmon, MITRE Corporation, October 1979.

Conversion of Oil Fired Industrial Boilers to Coal-Liquid Mixtures, MITRE Corporation, April 1981.

Converting SRC-II Process Product to Transportation Fuels, Chevron Research Company, August 1979.

Development of Alcohol-based Synthetic Transportation Fuels from Coal-Derived Synthesis Gases, Chem Systems Research and Development Group, August 1980.

The Development of Coal Burning Diesel Engines In Germany, A State-of-the-Art Review; U.S. Energy Research and Development Administration, August 1976.

Diesel Fuel Oils (BETC/PPS-7915), U.S. Department of Energy, Bartlesville Energy Technology Center, December 1979.

Electrification: A Dissenting View, Railroad Age, January 1981.

Exxon Donor Solvent Coal Liquefaction Process: Development Program Status; Exxon Research and Engineering; 1980 National Petroleum Refiners Association (NPRA) Annual Meeting, March 1980.

Fuel Extension by Dispersion of Clean Coal in Oil, U.S. Department of Energy, January 1979.

Future Propulsion Systems for Railroad Locomotives; Phase B Report; Advanced Diesel Engines and Laternative Fuels; Jet Propulsion Laboratory, December 1979.

Future Propulsion Systems for Railroad Locomotives, Phase C Report; Alternative Engines and Cost Analysis, Preliminary, Jet Propulsion Laboratory, California Institute of Technology, May 1981.

The Impact of Developing Technology on Indirect Liquefaction, The MITRE Corporation, April, 1981.

The Impact of the Toxic Substances Control Act (TSCA) on Commercialization of Fischer-Tropsch Products; Energy Resources Company, Inc., April 1981.

The Impact of the Toxic Substances Control Act (TSCA) on Commercialization of Fischer-Tropsch Products; Energy Resources Company, Inc., May 1981.

Inside EPA; January 2, 1981.

Inside EPA; February 20, 1981.

Liquefaction and Chemical Refining of Coal; Battelle Columbus Laboratories, July 1974.

Literature Survey of Properties of Synfuels Derived From Coal, Lewis Research Center, NASA, February 1980.

Methanol from Coal: Prospects and Performance as a Fuel and as a Feedstock; ICF Incorporated, December 1980.

Overview of Synthetic Fuels Potential to 1990, Cameron Engineers, September 1978.

Phosphoric and Fuel Cell Impact Assessment: Legislation Regulatory Incentives, Resource Availability, Technology Data Base (Draft), Energy Resources Company, Inc., February 1981.

The Population and Characteristics of Industrial/Commercial Boilers, PEDC Environmental, Incoporated, May 1979.

Power; The Coal Fired Alternative, Railway Age, May 11, 1981.

A Preliminary Review of Current Research Activities Bearing on Carcinogenic Effects of Coal Liquefaction, The MITRE Corporation, March 1979.

Proceedings of 2nd International Coal-Oil Mixture Combustion, Pittsburgh Energy Technology Center, November 1979.

Production of Methanol and Methanol-Related Fuels from Coal, Oak Ridge National Laboratories, ORNL-5564, May 1980.

Railroad Electrification in America's Future: An Assessment of Prospects and Impacts (Final Report), prepared for Department of Energy, Office of Transportation Programs, Washington, D.C., by SRI International, Menlo Park, California, January 1980.

Railroad Electrification: The Issues, proceedings of a conference held in Washington, D.C., on June 13 to 15, 1977, Transportation Research Board, Washington, D.C., NTIS No. PB-278538.

Recommended Federal Coal Liquefaction Program Plan, MITRE Corporation, December 1979.

Reducing U.S. Oil Vulnerability; Energy Policy for the 1980's, U.S. Department of Energy, November 1980.

Research and Development of an Advanced Process for the Conversion of Coal to Synthetic Gasoline and Other Distillate Fuels. Quarterly Technical Progress Report No. 7; U.S. Department of Energy, December 1978.

Research and Development of an Advanced Process for Conversion of Coal to Synthetic Gasoline and Other Distilled Fuels, Quarterly Technical Progress Report Suntech, Inc., February 1979.

Science and Technology of Coal Liquefaction and Coal Gasification; Trip Report Visits to Poland, West Germany and England, October 23 to November 25, 1978; U.S. Department of Energy, February 1979.

Solid Fuel Applications to Transportation Engines, Mueller Associates, Inc., June 1980.

Solid Fuel Railroading in the 80's? John H. Armstrong, Railway Age, October 13, 1980.

SRC I Coal Refining Demonstration Plant, Morris-Foster, International Coal Refining Company, October, 1980.

Standard Specification for Diesel Fuel Oil, ASTM, American National Standard ANSI/ASTM D 975-78, December 1978.

Surface Coal Gasification - Status of RD&D Activities and Facilities and Suggested R&D Program (Draft), March 1980.

Synthetic Fuels, Report by the Subcommittee on Synthetic Fuels of the Committee on the Budget, U.S. Senate, September 1979.

Synthetic Fuels Technologies; Cost, Product Quality and Environmental Data; Energy Resources Company, Inc.

Technical Aspects of Coal-Oil Mixture Combustion, U.S. Department of Energy, February 1978.

Technology Assessment Guides, DOE Office of Plans and Technology Assessment:
  No. 7, *Indirect Coal Liquefaction, Fischer-Tropsch Current Technology*.
  No. 8, *Mobil Coal to Methanol to Gasoline, Advanced Technology*.
  No. 10, *ICI Coal to Methanol, Advanced Technology*.

Telecon, Dr. David A. Berkowitz, American Coal Enterprises, and Mr. John T. Stone, Jr., Energy Resources Company, Inc.

Telecon, Don Gernery, U.S. Department of Energy, Bartlesville Energy Technology Center, and John T. Stone, Jr., Energy Resources Company, Inc., June 1981.

Upgrading of Primary Coal Liquids, Technical Memorandum, Fuel Research Institute of South Africa.

APPENDIX A

DESCRIPTION OF LIQUEFACTION PROCESSES

A.1 Lurgi-Ruhrgas Process

The Lurgi-Ruhrgas process is the only pyrolysis liquefaction process in commercial use. The low-pressure (1-atm) process was developed to liquefy European brown coal. The products of the process are 50 percent devaluatized char, 18 percent liquids, and 32 percent gases by weight. A 1,600-ton/day plant has been in operation in Yugoslavia since 1963. The liquid yield is approximately 1 bbl per ton of coal input, or about 1,600 bbl/day.

A.2 COED Process

The most developed U.S. pyrolysis process is the COED (char-oil-energy-development) process, which produces synthetic crude oil, gas, and char. COED is a multistage fluidized-bed pyrolysis process developed in the 1960's by the FMC Corporation under sponsorship of the U.S. Government. Successful operation of a 100-lb/hr process development unit (PDU) led to the design, construction, and operation of a 36-ton/day pilot plant that operated until 1974. Experience with this pilot plant indicated that scale-up of the process could be accomplished with little risk. A conceptual design of a commercial-scale plant was developed that would process 25,000 tons/day of Illinois No. 6 coal, producing approximately 28,000 bbl/day of 25 API syncrude. The output characteristics of COED are dependent on the coal characteristics, with highly volatile coals producing less char and more gas and oil. For typical bituminous coals, the output is about 20 percent gas, 20 percent oil, and 60 percent char by weight. The oils, hydrogen deficient and contaminated with ash, nitrogen, oxygen, and sulfur, require additional processing.

A.3 Occidental Pyrolysis Process

The Occidental Research Corporation (ORC) pyrolysis process is an entrained-flow process with very short residence times for molecules in the reaction vessel (1 to 3 sec) and with very rapid heating rates. Under development since 1969, a 3.6-ton/day pilot plant has been operated sucessfully on noncaking coals. Work is continuing to define a set of conditions - approximately 57 percent char, 35 percent liquids, and 8 percent gas, with a heating value of 700 Btu/scf - that will enable use of eastern bituminous caking coals to produce acceptable yield. The liquids are hydrotreated under pressure to produce either synthetic crude or low-sulfur fuel oil.

A.4 Flash Hydropyrolysis Process

The flash hydropyrolysis process being developed by Rockwell International involves very rapid heat-up and pyrolysis of coal under high-pressure hydrogen. Rocket technology was adapted for the production of liquids from coal. Operating at 1,600°F with 100-psig hydrogen over a 100-msec contact time, 35 percent of the carbon in bituminous coal is converted to liquids and 17 percent to methane. Current development work is being accomplished on a 24-ton/day PDU. The liquid products from the hydropyrolysis process require hydrotreating to produce marketable products. There are no reliable data on the amount and cost of this upgrading.

A.5 Direct Hydrogenation Coal Liquefaction Processes

Direct hydrogenation uses catalysts or solvents to aid in the transfer of hydrogen to coal. The Bergius (two-stage) process is the only direct-hydrogenation process ever used on a commercial scale. Between 1926 and 1943, 12 plants were built by the Germans, 2 by the British, and 1 by the Koreans. All of these plants were operated during World War II, with the German plants producing approximately 100,000 bbl/day of liquids, mostly aviation fuel. A demonstration plant constructed in Louisiana, Missouri, capable of 50 tons/day using the German technology, operated from 1949 to 1953. The Bergius process requires very severe operating conditions, with temperatures in excess of 900 F and pressures of 10,000 psig. This results in high capital costs with no potential for scale-up to economically viable capacities. Although the Bergius process is considered obsolete today many of the concepts are employed in modified form in the processes under active development.

A.6 Solvent-Refined Coal I

The four direct-hydrogenation processes closest to commercialization in the U.S. will be capable of supplying commercial quantities of synthetic liquids by the late 1980's. These are the solvent-refined coal (SRC) I and II, Exxon donor solvent (EDS), and H-Coal processes.

The SRC I process has advanced to the design stage of technical and economic demonstration. A 6,000-ton/day plant is being designed from information obtained in the operation of a 50-ton/day pilot plant at Wilsonville, Alabama. The status of the demonstration plant is uncertain due to the Federal budget and R & D policy constraints. If the demonstration program proceeds on schedule, the plant will be operational in 1986. The demonstration plant is designed to produce three products:

- A low-sulfur, low-ash solid product for direct combustion use
- An anode-grade coke
- A distillate liquid (from a two-stage liquefaction process)

This process produces a very low-ash (0.1%), low-sulfur (less than 1%) refined coal. The heating value of the solid is approximately 16,000 Btu/lb, which compares to an average bituminous coal heat content of about 12,000 Btu/lb. The process has been operated successfully with a variety of coals over extended periods. The yield of solid SRC is 60 to 65 percent of eastern bituminous coal by weight. The product has undergone successful testing in electric utility boilers; emissions were found to meet NSPS environmental requirements.

A.7 Solvent-Refined Coal II

The SRC II process has also progressed to the stage of large-scale demonstration. Developed by Gulf Oil Company, the SRC II process, produces a distillate syncrude. The process differs from SRC I only in that more hydrogenation is effected through longer residence times and slurry recycle.

The normal residence time for the coal in the reactor is about 1 hr. The hydrogen requirement is in the range of 4.5 to 5 percent by weight of the coal, depending on the coal used. The SRC II process has been successfully tested over extended periods of time with different coals at the 50-ton/day pilot plant located in Fort Lewis, Washington. The net yield of liquid per ton of coal in a balanced plant is approximately 2.5 to 2.8 bbl. The typical product slates are 15 to 20 percent gas, 45 to 50 percent distillate syncrude, and 35 to 40 percent residue by weight. The distillate syncrude generally contains less than 0.5 percent by weight of sulfur. A 6,000-ton/day plant, representing a single-process train of a commercial plant, is being designed; however, Government support for the planned construction of the plant has been withdrawn.

A.8 Exxon Donor Solvent

Development of the Exxon donor solvent (EDS) process, a proprietary process of the Exxon Donor Corporation, was started in 1966. A 1-ton/day PDU has been used to test the liquefaction characteristics of a large number of coals. A 250-ton/day unit has been operating satisfactorily since June 1980. Catalytic hydrogenation enhances the hydrogen donor capacity of the feed coal solvent slurry. The solvent transfers hydrogen from the hydroaromatic components of the solvent to the coal breakdown products in the preheater and reactor. Residence times on the order of 40 min have been used, producing a product slate comprising 15 to 20 percent gas, 33 to 35 percent C_4 distillate liquids, and 47 to 50 percent residue by weight. To aid in conversion, a modification will be made to the process to allow bottoms residue recycling. This modification will increase the production of higher value naphtha-type materials, with a corresponding reduction in liquids having boiling points above 800°F.

A.9 H-Coal Process

The H-Coal process is a single-stage catalytic process, as opposed to the solvent-based SRC I and II and EDS processes. The process has operated at a 2-1/2-ton/day PDU level for a number of years. A large-scale pilot plant capable of operating in syncrude or boiler fuel mode is currently operating. In the syncrude mode, 200 tons/day of coal is processed to produce a refinery feedstock. In the boiler fuel mode, 600 tons/day of coal is processed under milder conditions and at lower hydrogen consumption to produce a product that can serve as a direct substitute for No. 6 fuel oil. The large pilot plant has operated for approximately 1,500 hr (as of May 1981) in only the syncrude mode. A typical product slate from Illinois No. 6 coal, when operating in the syncrude mode, is about 10 percent gas, 53 percent distillate syncrude, and 37 percent vacuum bottom (high-molecular-weight residuals such as tars, which have little use) by weight. The distillate syncrude yield per ton of coal is about 3.2 bbl. The fuel has a sulfur content of about 0.1 percent and a nitrogen content of about 0.7 percent. The hydrogen consumption is in the range of 5.0 to 5.5 percent by weight of moisture-free coal. A project using the H-Coal process has been proposed to the Synthetic Fuels Corporation; a loan guarantee has been requested. The proposed plant would produce 25,000 bbl/day of distillate syncrude, with operation proposed for 1988.

A.10 Fischer-Tropsch Process

The Fischer-Tropsch process uses a synthesis gas produced by steam and oxygen gasification of coal, which can be accomplished in commercially available gasifiers such as the Lurgi and Koppers-Totzek. The synthesis gas is converted into a spectrum of products including pipeline gas, broad-boiling-range hydrocarbons, and oxygenated chemicals. Two types of Fischer-Tropsch reactors have been used commercially: fixed-bed (Arge) reactor and entrained-circulating-bed (Synthol) reactor. The fixed-bed reactor uses a pelletized-iron-based catalyst in vertical tube reactors operating at 25.5 atm, 220° to 255°C, and an H_2/CO ratio of 2.0. The reactor used commercially at the SASOL I facility produces 550 bbl/day of Fischer-Tropsch products.

The existing commercial Fischer-Tropsch technology can be deployed with minimum risk using the Lurgi gasifier. A cooperative agreement has been awarded for a Fischer-Tropsch plant under the first round of the Alternative Fuels Production Act (P. L. 96-126). This plant will use SASOL technology to produce 16,800 BOE/day of gasoline, diesel fuels, and jet fuel from 24,600 tons/day of Kentucky coal.

A.11 Mobil Methanol-To-Gasoline (MTG) Synthesis

Mobil Oil Corporation has developed a proprietary process for the conversion of methanol to high-quality gasoline (87 to 93 road octane number), using a high-selectivity, small-pore zeolite catalyst. The high selectivity results from the fact that the geometry of the catalyst physically controls the maximum size of the molecules formed. The process conditions are 775°F and approximately 2 atm. The highly selective catalytic reaction yields 44 percent hydrocarbons, 56 percent water, and traces of methanol, coke, and other substances. The process is highly exothermic, but temperature can be controlled with gas recycle in the fixed-bed reactor. A fixed-bed version of the MTG process tested at a laboratory scale of 4 bbl/day is judged to be commercial. New Zealand plans to install a 13,000-bbl/day MTG plant for gasoline production from synthesis gas produced from natural gas. Two feasibility studies have been awarded under the Alternative Fuels Production Act to investigate plants producing a total of 32,000 bbl/day of gasoline. The Lurgi and Koppers-Totzek gasifiers will be used to produce synthesis gas from coal. In addition, DOE has entered into a cooperative agreement to develop a preliminary design of a 50,000-bbl/day coal-methanol-gasoline plant. The process will use the Texaco gasifier. The Synthetic Fuels Corporation has received six proposals (as of August 1981) for projects using the MTG technology. A total production capacity of 165,000 BOE/day is represented by these proposed projects. Chances for funding within 1982, however, seem quite small.

A major advance in the MTG process, a fluidized-bed version of the process, is under development. Tested at a 4-bbl/day scale, this process will be further developed in a 100-bbl/day pilot plant in the F.R.G. under a cooperative agreement among DOE, F.R.G., and Mobil Oil Corporation. This development represents potential improvements in temperature control, recycle, and operating costs over the fixed-bed reactor system. Furthermore, by varying the residence time and catalyst construction, either diesel oil or jet fuel may be produced.

A.12 Methanol Synthesis

The production of methanol from coal is technically feasible; at least one commercial plant is in operation. Located in South Africa, this plant produces approximately 60 tons/day, using the Imperial Chemicals Industry (ICI) low-pressure (735-psig) methanol synthesis process and the Koppers-Totzek entrained-flow atmospheric coal gasifier.

In the U.S., the Synthetic Fuels Corporation has received five proposals to build methanol plants. In addition, six other plants are under study or construction. If all these plants were constructed and operated at design capacity, approximately 242,600 BOE/day of methanol would be produced from coal by the late 1980's.

The system for production of methanol from coal requires three essential component operations: coal gasification, gas steam clean-up, and methanol synthesis. Gasifiers of high throughput are preferred in the production of methanol, which implies that entrained-flow gasifiers are more suited to the process than either the moving-bed or fluidized-bed gasifiers. Entrained-flow gasifiers produce higher amounts of H_2 and CO and lower amounts of methane and hydrocarbons. This minimizes the build-up of inert species in the synthesis loop and avoids the problem of having to market the methane, a major product of the moving-bed gasifier. Operation of the gasifier at pressure minimizes the need for synthesis gas compression. Furthermore, because the gas from an entrained-flow gasifier has considerable heat in the gas stream, the integration of a gas stream heat recovery system with the methanol synthesis loop waste heat recovery system could provide an acceptable method to generate high-pressure steam for steam turbines coupled to air, oxygen, and recycle syngas compressors.

After the synthesis gas, which is rich in H_2 and CO, is produced in the gasifier, the raw gas is shifted to an H_2/CO ratio between 2.0 and 2.1. This gas is then purified to remove most of the CO_2 and sulfur compounds. The purification process must have ample provisions for coping with process upsets to prevent excessive amounts of sulfur and other impurities from reaching the methanol synthesis loop and thus poisoning the methanol catalysts. Gas stream clean-up systems used commercially, such as the Rectisol acid-gas removal unit, should present no technical problems in a methanol production system.

A.12.1 ICI Process

Two methanol synthesis processes dominate methanol production: Imperial Chemical Industries (ICI) and Lurgi. The ICI process accounted for 75 percent of the world's new production between 1966 and 1977. As already noted, the ICI process is used in the production of 18,000 gal/day of methanol from coal in South Africa.

The ICI process uses a copper-based catalyst in a low-pressure (50- to 100-atm) synthesis reactor. The synthesis gas feed has an H_2/CO ratio of approximately 2 and a sulfur level below 1 part per million by volume (ppmv). The main advantage of the ICI process is that it is adaptable to both large and small methanol plants (16,000 to 800,000 gal/day). The methanol product is slightly over 96 percent by weight methanol. Methanol of this purity is suitable for use as a fuel or as feedstock to the Mobil MTG process.

A.12.2 Lurgi Process

Development of the Lurgi methanol synthesis process was initiated in the late 1950's. The Lurgi reactor has an operating range of 30 to 100 atm at 200° to $300^\circ C$ and uses a copper-zinc catalyst. The synthesis gas has an H_2/CO ratio between 2 and 3 and a sulfur content of less than 0.1 ppmv. The crude methanol contains approximately 800 ppmv of methyl formate, 150 ppmv of ethanol, and 150 ppmv of dimethyl ether. The Lurgi process has an economic advantage over high-pressure processes because of decreased compression requirements. Furthermore, the reactor design permits direct recovery of the exothermic heat of reaction for steam generation for use in the plant.

A.12.3 Mitsubishi Process

There are a number of other methanol processes in commercial use. These

COAL AS A RAIL FUEL:

AN ASSESSMENT OF DIRECT COMBUSTION

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COAL AS A RAIL FUEL:

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PREFACE

The study reported herein was funded entirely by American Coal Enterprises, Inc. The engineering and environmental analyses presented herein were based on the general design criteria being used by American Coal Enterprises. The report is a documentation of readily available information which was assembled and analyzed during a two month period.

The authors wish to acknowledge the special effort of Ms. Marian Jones, Assistant to the Director, and Roman Olynyk, Technical Editor, of the WVU Energy Research Center staff, for editing and producing the final manuscript of this report.

EXECUTIVE SUMMARY

Railroads are critically important to the United States. More than one-third of the nation's ton-mileage goes by rail. Items such as food, fuels and manufactured goods which are crucial to maintaining a high standard of living and adequate national security depend on rail haulage. Yet, America's railroads are fueled almost exclusively by oil. Thus, railroads are an important segment of the nation's transportation system which should be considered for conversion from oil.

Of the several alternatives available for reducing the rail system's dependence on oil, the possibility of converting to the direct combustion of coal has many attractive features. This report presents an assessment of economic and environmental factors involved in such a conversion. General engineering and environmental analyses are presented in which design parameters are taken to be those believed possible using modern technology.

The use of coal is found to offer several direct economic benefits to the operating companies as well as numerous indirect benefits to the entire nation.

Analyses found that present federal environmental standards can be met by direct coal-fired locomotives provided that modern combustion and control technology are utilized.

National security would be greatly enhanced by conversion of the rail system to coal as the fundamental fuel. Moreover, a switch to the direct combustion of coal is shown to offer the quickest possible large scale conversion from oil -- an important economic and security consideration.

More specifically, from the information presented in this report, it is concluded that the use of coal combustion locomotives will:

1. permit a low-cost fuel for 90-95 percent of the rail system where electrification is not feasible during the remaining years of this century;
2. free the railroads of the political uncertainties associated with foreign oil supplies and the associated adverse effects of drastic price increases;
3. reduce oil imports and free supplies of diesel oil for use in other transportation modes that are unable to burn solid fuel;

4. have a positive effect on the nation's balance of payments;

5. reduce fuel cost on any railroad line by about 35 percent, including the costs of fuel handling;

6. save the rail industry nationally $1.3 billion per year in fuel cost at present traffic levels, if present diesel locomotives were all replaced with coal-fired locomotives;

7. provide employment for approximately 15,000-20,000 additional miners;

8. have a positive effect on the coal market because of the stable demand for coal by the railroads;

9. require about 35 to 50 million additional tons of coal production per year which can be easily produced with present over-capacity;

10. meet present or anticipated federal environmental standards by using present-day combustion and control technology;

11. not change the sulfur dioxide emission total of the railroad transportation system, if available low-sulfur coal is used;

12. meet more stringent future regulations, especially for sulfur emissions, with expected future development;

13. enable the railroads to cope with real economic growth in both export and domestic trade;

14. permit gradual phase-in and be compatible with current railroad operating practices;

15. provide locomotives that are as reliable, automatic, convenient and simple for a crew to operate as diesel locomotives;

16. permit several diesel and coal locomotives to be operated in tandem by a single operator;

17. have maintenance costs that are about the same as for expected future diesel locomotives;

18. cost about the same in capital as replacing old diesels with new or more efficient diesel designs;

19. require about the same amount of labor for operation and maintenance as diesels.

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I. INTRODUCTION

As a result of the successful introduction of diesel locomotives, the development of coal-fired steam locomotives ceased in the United States in the 1950s. However, steam technology continued to advance in this country and overseas, particularly in utilities. In a few countries, new designs of railroad steam power in the 1940s and 50s achieved useful fuel efficiencies as high as 12 percent, a level substantially greater than the five to seven percent characteristic of the last U.S. steam locomotives built in any large numbers [21].

In the 1950s, both turbine and new reciprocating steam locomotives achieved fuel efficiencies well over 10 percent, but the low price of diesel fuel gave diesel locomotives a substantial edge in fuel cost per ton-mile.

Since 1950, steam technology has continued to improve. Advances have been made in combustion air control, furnace efficiency, steam flow path design, heat recovery equipment, and in cylinder and transmission efficiency.

Besides technological advances, other circumstances have changed since the end of steam power on U.S. railroads. Environmental factors such as pollution and noise are now stringently regulated. Railroad operating requirements have changed, and fuel oil prices have increased dramatically. From 1950 to 1973, the cost of energy from oil relative to coal was dropping, favoring the shift from coal to oil. Since 1973, however, both oil and coal prices have risen. During the past year, oil prices escalated so rapidly that at present a unit of energy from oil is nearly four times as expensive as a unit of energy from low sulfur coal.

The purpose of this study is to determine whether the application of present day technology to the development of a coal-fired locomotive could result in a machine that is competitive with diesel-fueled locomotives. The report presents a preliminary assessment of economic and environmental factors involved in a conversion of the nation's railroads from diesel to coal. General engineering and environmental analyses are presented in which design parameters are taken to be those believed possible by using modern technology.

II. POSSIBLE ALTERNATIVES

The dependence of the railroads on fuel oil can be alleviated by one or more alternatives. Four alternatives and a discussion of each follows.

1. **Modify present diesel engine designs to burn fuel oil more efficiently.** This choice offers only a slight impact on reducing the adverse effects of oil dependency. In any case, this alternative involves considerable research and development and could not provide any impact until the mid 1990s at the earliest [1].

2. **Burn synthetic fuels in conventional or new diesel locomotives.** Although this is a viable engineering solution in the longer term, the fact remains that synthetic fuels production will not reach 500,000 barrels of crude per day until at least 1987 and two million barrels per day by 1992 [2]. Thus the synthetic fuel alternative could not offer a significant impact until the mid 1990s and the railroads would still be removing liquid fuels from the marketplace, competing with other users of liquid fuels for the stocks available [4].

3. **Electrify the railway system.** Electrification is feasible on only a small portion of the U.S. railway system. Not more than five to ten percent of the total system can be electrified economically. Costs of electrification on a national basis are so great that the required capital is not available and will not be realistically available during the remaining years of this century [3, 5].

4. **Direct combustion of coal.** In view of a realistic appraisal of the alternatives above, the direct combustion of coal on board locomotives offers the greatest probability of a significant reduction of the railroads' dependence on oil before the year 2000. The application of state-of-the-art technology to a coal-fired locomotive design could yield a prototype in one to two years, with full production beginning as early as two years later. Thus, if development were begun in 1980, a significant impact could be expected in the 1985-1990 time frame -- much earlier than the alternatives above. The added feature of placing the U.S. rail system on a domestic fuel supply as early as possible has obvious national security advantages.

III. THE CURRENT SITUATION

A. Railroads: A Critical Means of Freight Transportation

Many transportation modes — highway, water, air, pipeline and rail — are needed in a modern society. But no other mode can displace the railroad as an efficient and effective mover of certain bulk commodities and other items. In the United States railroads carry the largest share of freight. Figure 1 shows that in 1979 more than one-third of all intercity ton-miles of freight moved over the rails. The railroads' share of freight has been quite stable since 1975 and has risen slightly to 36.6 percent of the total intercity freight in 1979 (see table 1).

Railroads haul as much as two-thirds of the nation's annual tonnage in such commodities as coal and grain. These commodities are crucial to the energy, export, food, and industrial needs of this and other nations. Yet the railroads must rely almost exclusively upon oil -- a fuel which is in short and uncertain supply. Oil has many other uses in several other modes of transportation and in agriculture, commerce, and industry. If coal could be substituted as the basic railroad fuel, this adequate and dependable domestic fuel would erase energy uncertainties for railroads in the decades ahead.

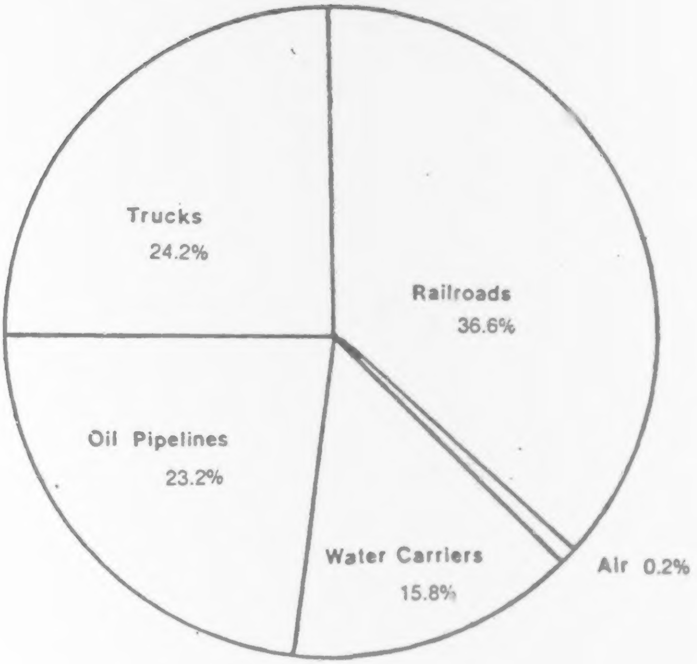
Comparison of the amounts of middle distillate fuels used by the railroads with the amounts used by other consumers can be misleading. The railroads consumed 4.3 billion gallons of fuel last year, yet they do not use as much fuel as highway vehicles, or nonmilitary aircraft, or heating (see figure 2). In 1977, the year of the latest complete data, railroads consumed only 6.2 percent of the total middle distillates used in the country. That was more, however, than was needed for agriculture, construction and certain other uses which cannot turn to a solid fuel substitute.

B. Rail Electrification

Since World War II, railroads have depended upon diesel oil as their primary fuel with the exception of a small number of lines that use electricity. Today, less than one percent of rail mileage is electrified, and in the next two decades five to ten percent of U.S. track miles might be electrified. A Gibbs & Hill study completed in November 1979 estimates that the initial capital investment for electrification of Conrail's main track between Pittsburgh and Newark would be nearly $1.2 billion. This huge front-end cost would cause a negative cash flow for the first five years before savings could be realized [3].

FIGURE 1

INTERCITY FREIGHT TON-MILES: 1979



Source: Association of American Railroads

TABLE 1

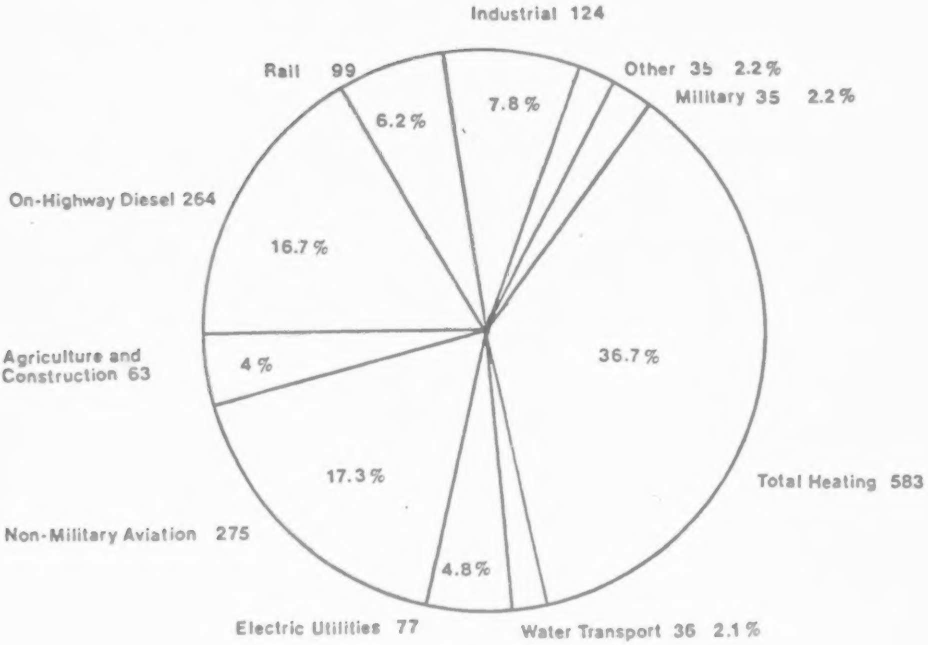
RAILROAD SHARE OF INTERCITY FREIGHT TRAFFIC

	Percentage of Intercity Ton-Miles				
Year	Railroads	Trucks	Water	Oil Pipelines	Air
1970	39.8	21.3	16.4	22.3	0.2
1971	38.2	22.8	16.1	22.7	0.2
1972	37.8	22.7	16.3	23.0	0.2
1973	38.4	22.6	16.1	22.7	0.2
1974	38.6	22.3	16.1	22.8	0.2
1975	36.7	22.0	16.5	24.6	0.2
1976	36.3	23.2	16.9	23.4	0.2
1977	36.1	24.1	15.9	23.7	0.2
1978	35.8	24.8	15.8	23.4	0.2
1979(prelim)	36.6	24.2	15.8	23.2	0.2

Source: AAR, The Economic ABZ's of the Railroad Industry, Table IV-3

FIGURE 2

U.S. MIDDLE DISTILLATE USERS: 1977



Note: figures indicate millions of barrels

Source: Association of American Railroads

Capital needs of the railroads for the 1980s are great. U.S. Department of Transportation studies conclude that by the middle of the decade the industry, not including government-backed Conrail, will be $13 to $16 billion short of the funds needed to replace tracks and rolling stock and to repay existing debts on schedule [5]. Therefore, if the use of coal as a rail fuel is to be widespread, coal must show a large operating savings and quickly amortize capital investment.

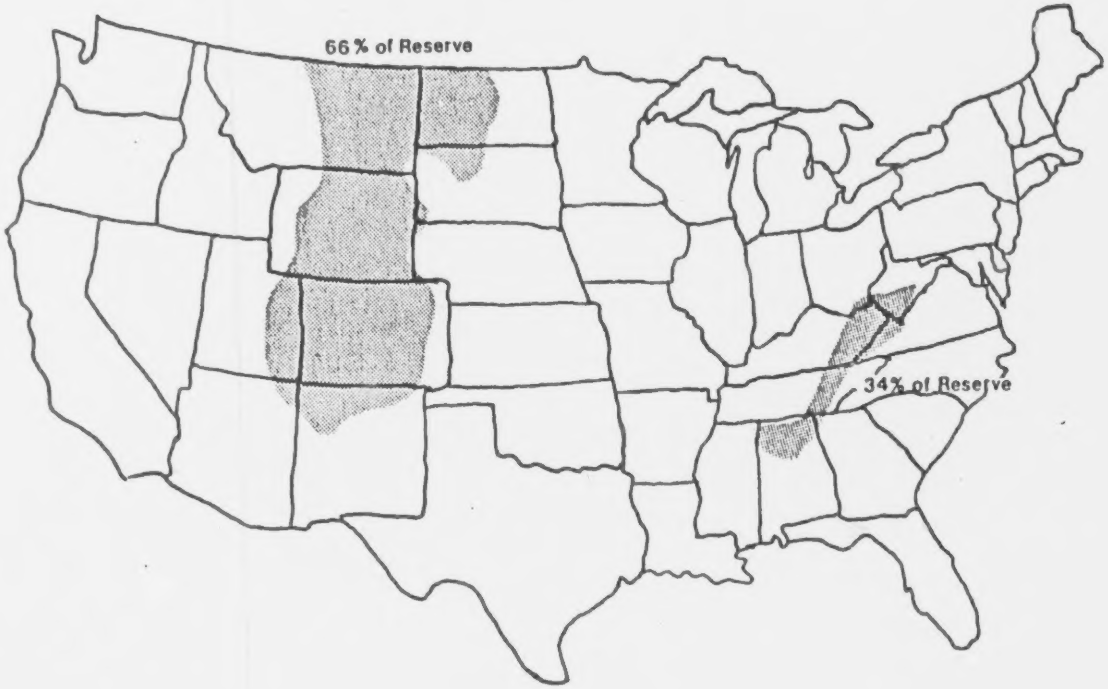
In light of apparent benefits vs. costs, electrification will be limited to certain select routes with very high traffic densities. Extensive electrification of tracks throughout most of the country is unlikely to occur in this century. The focus of the present West Virginia University study is on the 90 to 95 percent of U.S. railway mileage where direct combustion of coal will be a less costly fuel than oil or electricity.

C. Availability of Coal

The most appealing aspect of coal is its availability in large quantities and its widely scattered distribution in the United States. No other country has such extensive reserves of high and medium quality coal so well distributed among geographic regions. About two-thirds of all coal mined in the United States moves over the railway systems; this is about one-third of all rail freight tonnage. Until the 1970s, significant coal production was limited to the fields of the Appalachian region and the Middle West. Nearly all coal consumed was in the coal-producing states and bordering states of these regions. The average distance coal was hauled was about 255 miles, with little of it going more than 300 miles. Now, however, the average length of haul is close to 400 miles, with coal mined in the West moving an average of 650 miles. In fact, coal is moving as much as 1,800 miles from certain western mines to power plants in the South and Southwest. Although coal is a commodity that is heavy relative to its value, its net cost to the user is less than for oil.

The distribution of coal reserves and coal mines is a factor which increases the desirability of having the railways use coal as their basic fuel. The proven reserves of coal in the United States total 184 billion tons [8]. The regions of the West and the southern Appalachian region shown in figure 3 hold the nation's low-sulfur coal deposits. Many large railroads, such as Chessie System and Norfolk & Western in the East, and Burlington Northern and Union Pacific in the West, own extensive coal reserves. Coal supplies will be more readily available to these and other systems if the rail mergers currently under active consideration are com-

FIGURE 3
U.S. LOW SULFUR COAL RESERVES



Source: U.S. Department of Energy

pleted. This means that many of the nation's railways will have ready access to sufficiently large reserves within the territories they serve and will be able to meet their fuel needs for at least the next half century. This is an important factor in minimizing transport costs for the coal consumed by each railroad.

IV. ECONOMIC ASSESSMENT OF COAL AS A FUEL

A. Coal: A Domestic Product

An assured supply of energy has never been more important to the nation than it is now. Coal is both widely distributed and in large reserve. Coal supplies are stable compared with oil from the Middle East, Africa, Asia and South America. The transport system that hauls coal to consumers is domestic, and the machinery used in coal production is provided by American manufacturing firms.

With the nation's continued dependence upon foreign oil, coal's availability from domestic sources takes on even greater significance. A Harvard Business School energy study noted that the "true marginal social cost of imported oil is not only higher than the regulated domestic price, it is at least double even the OPEC price" [7], because of the balance-of-payments deficit incurred and because of the lost domestic employment in fuel-producing industries.

While the term "marginal social cost" cannot be measured precisely, the concept is widely known and is an important public policy consideration. For example, even if Btu-cost differences between coal and oil were less than they are now, the assurance of stable, adequate supplies of domestic coal for all railways for many years into the future could prove to be more important than the cost differences. This consideration is of special significance when attempting to establish a realistic benefit-cost ratio for coal versus oil.

B. Stability of Railways as a Market for Coal

Coal as a railway fuel can be a stable and growing market, distributed widely throughout the country. While the rail market cannot approach the size of the electric utilities market, it could nevertheless be sizable, possibly ranging from 35 to 50 million tons each year, and this can be phased in gradually.* This annual consumption compares to over 700 million tons produced in the United States in 1979.

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*The amount of coal that would be consumed if it were to replace diesel oil as a railway fuel was computed on the basis of 13,000 Btu/lb. for coal and 141,500 Btu/gal. for oil. If a new generation of steam locomotives were assumed to require about twice as many Btus to produce a gross ton-mile as diesels now in service, 47 million tons of coal would be required to replace the amount of diesel oil used in 1979. Increased rail traffic in future years would require somewhat larger amounts.

Despite steadily increased total ton-mileage on railroads, the amount of fuel consumed each year for the past decade has increased little, with year-to-year changes being small (table 2). Increased fuel efficiency has been a factor in the small increase in total fuel consumption and some additional fuel efficiency should be anticipated. Yet, future increases in coal and grain traffic are expected to more than offset fuel efficiency increases and result in increased total consumption. Table 3 shows the gross ton-miles per gallon of diesel fuel in the past decade. Efficiency increases seem reasonable in the present decade with advanced diesels, but the large price differential between oil and coal fuel cannot be overcome by the increased diesel engine fuel efficiency anticipated by diesel builders [7, 1].

C. Employment Effect

Output per man-day varies widely between underground and surface mines in the same region and between similar types of mines in different regions, such as those of the Appalachian fields and those of the Powder River Basin. The greatest production increases are projected to be in the West where output per man-hour is highest. But coal will be needed for trains of the East and Midwest where mining productivity is relatively lower per man-hour. The expanding coal use, however, should occur over time on a gradual basis, allowing sufficient time for mining capacity adjustments to take place in an orderly, efficient and stable manner. In this sense the railroad market for coal fuel would prove to be extremely desirable in terms of both size and dependability.

Stability in coal demand has been demonstrated among the electric utilities, but exports and consumption by industrial users have varied widely over time. While coal exports and use of coal by steel, chemical, and other industries will increase, stability of the type that would be found in the railway market is unlikely. Furthermore, the railroads could become the second or third largest market for coal, following electric utilities and exports. This relative position could change, however, if the export market advances to the extent suggested by the recent World Coal Study, and a large surge in steam coal exports to Europe begins [8].

The coal industry now has the capacity to mine an additional 100 million tons of coal per year. At a railroad fuel consumption rate of 35 to 50 million tons of coal each year, 15,000 to 20,000 new miners could be employed at current productivity rates. Cur-

TABLE 2

RAILROAD DIESEL FUEL CONSUMPTION

Year		Gallons Consumed (millions)
1970		3 808
1971		3 823
1972		3 997
1973		4 161
1974		4 175
1975		3 736
1976		3 896
1977		3 895
1978		3 968
1979	preliminary	4 300

Source: AAR, The Economic ABZ's of the Railroad Industry (Table V-7)

TABLE 3

RAILROAD FUEL EFFICIENCY

Year	Gross Ton-Miles Per Gallon of Diesel Fuel
1970	520
1971	493
1972	496
1973	507
1974	510
1975	507
1976	511
1977	513
1978	524
1979 preliminary	536

Source: AAR, The Economic ABZ's of the Railroad Industry (Table V-4).

rently, 20,000 miners do not have jobs, and many open mines in the East run only one shift per day [9]. The number of employed miners can be higher if more underground Eastern coal is mined. Much of the coal, however, will be from the West, where output per man-day at some mines exceeds 100 tons, compared to 10 tons per man-day for many of the older mines in Eastern fields. The total employment estimate is based on an average of 15 tons per man-day nationally, meaning that actual employment could differ widely from this if the additional production needed for locomotives is concentrated in fields with daily outputs per man that vary significantly from the national average.

D. Growth in Rail Freight

Railway freight traffic is likely to increase on a ton-mileage basis. Growth in coal tonnage moving by rail, as well as growth in average length of haul, is a virtual certainty. Grain traffic must increase also, with the greatest probable growth being in exports, meaning that the distance of haul will be long. This country is able to provide quantities of coal and grain well above those needed for domestic consumption, and the nation can do this on a sustained, long-term basis. Railway Age reported in 1980 that grain loadings for the first 22 weeks of the year were up more than 23 percent over the same period in the previous year. While weather conditions affect grain harvests from one year to the next, the trend, like that of coal, must be upward [10].

Increased coal exports are causing concern because of congestion at East Coast ports, especially at Baltimore, Hampton Roads, and Philadelphia. References to "a possible tenfold increase in global [Europe and Japan] coal imports by the end of the century" raise questions about the ability of transport systems to cope with volumes of that magnitude [6]. Much of this coal will have to be hauled by rail to Atlantic and Gulf ports.

Slurry pipelines will carry increasing amounts of coal, but it is likely that railroads will continue to carry the overwhelming portion of it. Per unit of capital investment, the railways can expand volume and react to market changes more rapidly than slurry pipelines. In addition, traffic expansion is anticipated for coal moving by rail to Atlantic ports for coastal ocean hauls to electric utilities in New England that have depended in the past upon residual fuel oil [6].

Some shifting of traffic currently being moved by other carriers to the railways seems probable, especially in times of fuel emergencies. Petroleum shortages and anticipated price increases are not yet causing shifts from highway carriers to the rails, but trucks operating on the highways have no fuel source other than oil. All studies justify the conclusion that railways are more energy efficient for long-distance, high-volume traffic than are trucks. Table 4 indicates that railways are about four times as efficient as trucks, on the average. In times of low-cost, readily-available fuel, this relative efficiency was of minor importance, but high-cost, limited oil supplies create different circumstances.

Even short of emergencies, low rail fuel costs can attract more traffic. If railroads can go to a lower-cost fuel, more truckers can piggyback their trailers and cut their costs, since rail piggyback can be more economical. These lower costs could then attract more trailer traffic off the highways, which would cut highway maintenance costs. Lower rail fuel costs can also keep rail rates down, thereby lessening upward pressure on rail rates for hauling coal to electric utilities.

The rail system has the capacity to cope efficiently with more traffic in all commodities and to adjust its capacity as rapidly as other industries can enlarge their productive capacities.

E. Price Stability and Relative Fuel Cost

Coal and oil prices have risen significantly during the past decade as shown in figure 4. Coal experienced significant price increases during 1974 and 1975 and has risen slowly since. Oil, on the other hand, has experienced steady increases since 1974 with a more rapid rise after 1978. Despite these differing fluctuations, coal has continued to cost significantly less than oil on an equivalent energy basis (price per Btu) throughout the decade. In 1980 the cost differential between low-sulfur coal and diesel fuel oil has risen to a factor of roughly 3.7 at the time of this publication. For example, low-sulfur Eastern coal appropriate for fueling a locomotive costs approximately $1.58 per million Btu delivered [18], whereas oil is selling for about $5.87 per million Btu in large quantities to railroads [17]. Continued increase of this differential is expected until synthetic fuels become competitive with imported oil in the 1990s. Meanwhile, the current excess domestic coal mine capacity will limit further coal price increases during the next few years. In any case it appears that coal prices will remain significantly lower than oil on an equivalent energy basis through the end of this century.

TABLE 4

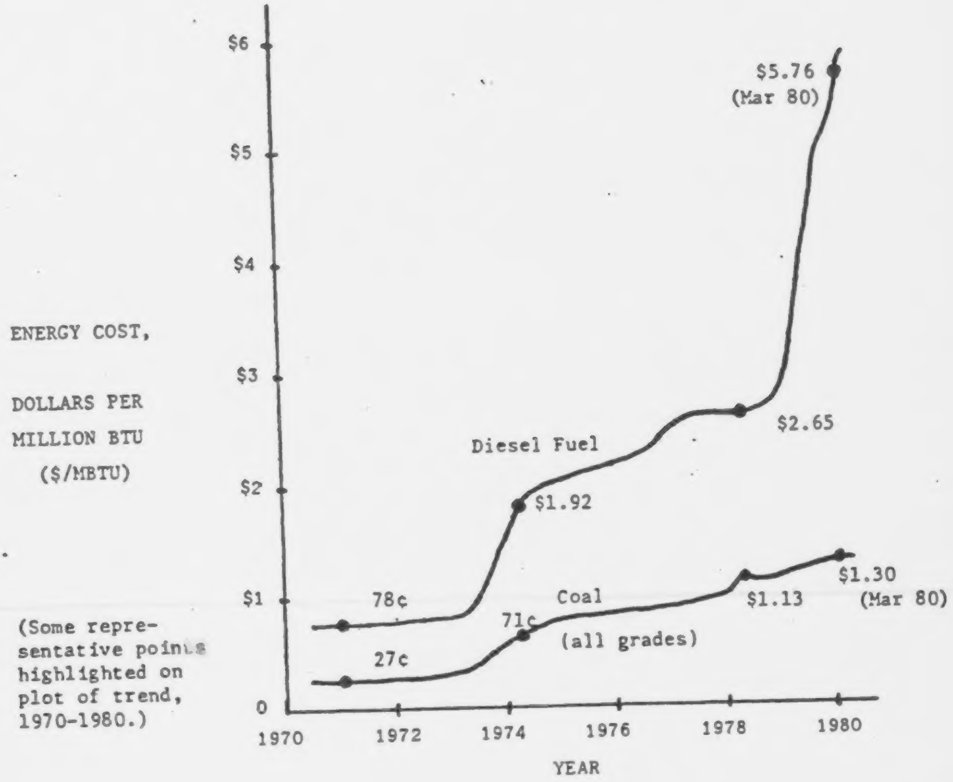
ENERGY INTENSIVENESS: BTU PER NET TON-MILE

	MODE				
Investigators	Pipeline (oil)	Rail-road	Water-way	Truck	Air
Hirst (1973)	450	670	680	2,800	42,000
Railway Age (1973): Battelle's Columbus Labs	---	536-791	---	2,518-2,800	---
Railway Age (1973): Missouri Pacific's Traffic Research Division	---	500	---	1,800	---
Mooz (1971)	1,850	750	500	2,000	63,000
Reading Railroad Data	---	140-1920	---	---	---

Source: Transport of Solid Commodities Via Freight Pipeline, V. 5, (July 1978), p. 12.

FIGURE 4

AVERAGE ENERGY COST COMPARISON FOR COAL AND DIESEL FUEL



Sources: Department of Energy, Wholesale No. 2 Diesel Price Averages; Coal Price Averages Delivered to Utilities. (Monthly Energy Review.) Association of American Railroads, Economic ABZ's of the Railroad Industry, Table III-7.

F. Operation of Railroads During Times of Oil Shortage

If railroads continue their almost exclusive dependence upon oil as their fuel source, they remain as vulnerable as other industries to changes in oil production and prices on a worldwide basis. In other words, the more than one-third of our intercity freight hauled on the rails is as vulnerable as the rest of our commerce. In addition, the railways will have to compete with the other essential users of petroleum products. If, however, the railways were to use coal as their fuel, an oil-related interruption of rail service would not occur. The railroads would not be competing with road carriers, industrial users, and farmers for limited oil supplies. In fact, the railways would be able to support oil-consuming industries by assuming some of their traffic burdens on a temporary, short-term basis.

The railways are unique relative to other transportation systems in their potential ability to use coal directly as their principal fuel. The coal can come straight from a conventional preparation plant at the mine and need not be converted to liquid at additional cost. Neither trucks, autos, aircraft, nor agricultural vehicles can use solid coal directly under the present state of technology. This was noted in the 1979 Ford Foundation study on energy use, which stated that "cars, buses, and agricultural vehicles are not going to burn anything but liquid fuel within the next couple of decades [7]." Railroad fuel consumption now accounts for 100-110 million barrels of crude oil per year, which could be released to other modes.

In the 1990s direct burning of coal on railways would also free synthetic fuel oil for other transportation modes. This could become very important, since the availability of middle distillates refined from coal is not likely to be great enough to meet the needs of transportation systems during that time frame.

G. Oil Demand and Availability

Figure 2 of this report shows the wide range of uses of middle distillates, with the railroads consuming slightly more than six percent of the total. The largest portion, more than one-third of the total, is used for heating. More than 16 percent is consumed on the highways and a larger portion by the aviation industries. Electric utilities, agriculture, construction, industrial, military and other users depend heavily upon the middle distillates. Few, if any, of these can use substitutes in any reasonably effective manner. Yet, increased conservation and more conversion to readily available domestic energy sources are extremely important to the nation. Any one of the user groups that can find an acceptable substitute should convert as soon as feasible.

Synthetic fuels have the potential to make a significant contribution without changes in the user's plant. However, only a few experimental synthetic conversion operations are currently in existence, and at least a decade will pass before synfuel production can have a significant impact on world energy supplies. The maximum expected flow of synthetic oil equivalent from domestic coal is one to two million barrels by 1990, and only a small portion of that production will be in actual liquid fuel. Most synthetic fuel will be in the form of natural gas substitutes. In the meantime, a Harvard Business School study noted that it is unreasonable to expect domestic production of oil from "conventional sources" to be increased very much, if at all, during the rest of this century [11].

H. Oil Backout: Railroads and Utilities

About one quarter of all energy in the United States is consumed by transportation. At the same time, fuel price rises have been greater than have other transportation cost increases. This fact becomes more critical when the only other possible significant near-term substitution of coal for oil is in the electric utility industry. Further, the oil used in generating electricity is almost exclusively residual fuel oil that has limited uses, rather than diesel oil, which has a variety of uses in transportation and other industries. Having the railroads substitute coal for diesel fuel would be a more important development on a per-barrel basis than would substituting coal for residual fuel oil that is limited in use to electric utility and certain industrial boilers. (See F.)

I. Political Considerations

The widespread concern about the uncertainty of oil is evident to most serious researchers and analysts in the energy field. Nowhere has this been stated more succinctly than in the Harvard study: "The U.S. is becoming increasingly dependent on foreign oil supplied by countries that are increasingly unstable [12]." This was emphasized further by Walter Levy in the Summer 1980 issue of Foreign Affairs:

> ...what has dominated international oil relations has been the fear of importing countries and their companies that OPEC may cut off their

> supplies, or impose stiffer conditions at the slightest sign of resistence or of a common policy approach by importing countries [13].

The Ford Foundation energy study notes that oil is "the fuel most vulnerable to interruption in supply" and that the "reserves are distributed with remarkable unevenness over the earth, nearly half being in politically unstable countries [7]."

This situation is a distinct contrast with the degree of stability in coal supplies, prices, and availability from domestic sources that can be sustained over many decades. The lack of stability in several major oil-producing countries is causing substantial economic and political costs to this country. Political cost can be just as devastating as economic costs if supplies are interrupted over long periods of time or are cut off entirely. A significant portion of this impact could be drastically lessened by having the railway system of the United States shift from oil to coal as its principal fuel.

V. ENGINEERING COST ANALYSIS OF A NEW COAL-FUELED LOCOMOTIVE

Diesel-electric locomotives are the major power units for U.S. rail service. Except for some electric locomotives, used on a few portions of electrified track in the high-density Northeast corridor and on some specialized railroads, the diesel serves the entire country. More than 99 percent of rail ton-miles in the United States are diesel hauled [17]. Thus, diesel engines are selected for comparison with a proposed coal-fired reciprocating locomotive.

The two-stage, gas-producer combustion system is a proven method of combustion, and it has been tested in locomotive use. More recently, fluidized bed combustion has been the subject of much research. However, development of a practical fluidized bed system which could work reliably in the rugged and severe railroad environment is years away. Many technical issues remain. Development of a practical fluidized bed combustion system on railroads would benefit from prior experience with new coal locomotives which could be built and put into large-scale service now. Another factor needing consideration is the form of transmission of heat to mechanical energy. An obvious option is the steam turbine. Such turbines, however, have never proved fully practical in railroad fleet service for everyday, broad-scale duty, despite much effort in the past both in the United States and overseas to apply steam turbines to railroads [21]. To be practical, any serious proposals to put direct combustion to daily use on railroads must address these technical problems.

The proposed coal-fueled locomotive is a two-stage combustion, reciprocating type. It is planned for heavy-duty freight service and is comparable to a diesel locomotive designed for similar service. From the large number of available diesel locomotive models, a new, current-model, four-axle freight design may be chosen for comparison because it is the most popular model used in heavy freight service. It has the latest operating features, and it has improved thermal efficiency. Such a locomotive usually has 3000 shaft horsepower available for traction, driving an electric alternator connected to electric motors on the axles. The efficiency of the electrical drive train together with frictional losses theoretically give about an 85 percent transmission efficiency for this type of engine, but railroads generally have learned to expect an 80 percent transmission efficiency between prime mover and pulling coupler (drawbar). A recent Jet Propulsion Laboratory study rates the engine shaft thermal efficiency of a modern diesel in rail service at 38 - 40 percent maximum when burning No. 2 diesel fuel [1]. Hence, the maximum thermal efficiency of a new diesel at the drawbar is about 32 percent. (40 percent shaft efficiency x 80 percent transmission efficiency = 32 percent drawbar efficiency.)

A proposed coal-fired locomotive may be expected to deliver 3000 to 4000 horsepower to the drawbar over a wide range of speeds. The maximum expected drawbar thermal efficiency is about 18 percent, but an average drawbar efficiency of 15 percent will be used for comparison. The axle load will be a maximum of 30 tons per axle. The range of the engine will be about 500 miles without service, with the engine consuming 31 tons of coal and using half of its make-up water. The designers believe the proposed locomotive can be built to these specifications and be operating by 1983 in a tightly scheduled development and construction program.

A. Energy Balance From Fuel Source to Rail

It is interesting to compare the thermal efficiencies of coal and diesel locomotives from fuel source at mine or oil well to final work at the drawbar.

Diesel Locomotive. The fuel for diesel engines is normally a high-quality No. 2 diesel fuel or fuel oil. The net energy efficiencies to produce energy at the rail are approximately as follows:

Oil Production	98%
Oil Refining	93%
Transportation	98%
Diesel Loco. Eff.	32%

This net balance gives an overall thermal efficiency of 28.6 percent at the drawbar for a current diesel locomotive.

Coal-Fueled Locomotive. The coal-fired locomotive will normally use coal sized from one-half to two inches and containing a maximum of one percent sulfur. Large supplies of this type of coal exist in both Eastern and Western coal regions. In producing rail energy from coal the following efficiencies are relevant:

Coal Production	98%
Coal Transport	98%
Coal Loco. Eff.	15%

This net balance gives an overall thermal efficiency at the drawbar of 14.4 percent for the proposed coal-fired locomotive. Note that, because of the small energy losses involved in coal production, there is little drop from the locomotive's efficiency of 15 percent to the overall thermal efficiency of 14.4 percent. (See the next paragraph below.)

B. Coal Synfuel for Diesel Engines

Modern processes are being developed for the production of liquid fuels from coal. These higher-efficiency processes usually have thermal efficiencies of conversion of about 70 percent net of all inputs and losses. In such conversion, the efficiencies involved are:

Coal Mining	98%	
Coal Transport	99%	
Coal Conversion	70%	(Syncrude)
Final Refining	90%	(Diesel-Quality Fuel)
Oil Transport	98%	
Diesel Loco. Eff.	32%	

This gives a 19.2 percent overall thermal efficiency for a diesel engine burning a coal-derived, high-quality diesel fuel. Note the significant drop from the locomotive efficiency of 32 percent to the overall efficiency of 19.2 percent, which reflects the losses in converting coal to liquid fuel. Whereas the ratio of diesel to steam locomotive efficiencies is about 2.1:1, (32 percent to 15 percent), the overall efficiencies are closer to each other, at 1.3:1 (19.2 percent to 14.4 percent). The relative inefficiency of steam is partly compensated by the inherent extra costs of converting coal to liquid. Newer diesels with higher locomotive efficiencies running on synfuel will be affected by the same coal-to-oil conversion costs. Along with thermal efficiencies, therefore, prices of the fuels must be assessed.

C. Fuel Cost Comparison

The relative cost of fuel to produce useful work at the drawbar can be found directly by knowing (1) the locomotive engine thermal efficiency measured at the drawbar, and (2) the cost of fuel per Btu loaded on board the locomotive. Under equal conditions of everyday service, the modern diesel-electric locomotive is assumed to have a thermal efficiency of 32 percent at the drawbar (40 percent at the shaft for traction x 80 percent for all electrical, mechanical, and friction losses), and the modern coal-fueled locomotive is assumed to have a thermal efficiency under the same working conditions of less than half this amount, or 15 percent (see p. 22).

The absolute thermal efficiencies are not as important for purposes of relative comparison as the relative difference assumed between the two types of locomotives. The figure assumed for steam is intended to be conservative, and the ratio of efficiencies between diesel and steam is expected to remain roughly constant over the next decades as both diesel and steam improve.

As of spring 1980, railroads were paying a contract price of 82¢ per gallon for diesel fuel, or about $5.87 per million Btu [17]. Coal buyers in the mid-Atlantic region were paying a delivered price of about $1.58 per million Btu for low-sulfur coal [18]. Post-delivery railroad handling costs (see p. 26) are assumed to be about 15¢ per million Btu for diesel fuel and would be about 26¢ per million Btu for coal. The latter value is intended to be conservative. Thus, the total cost per million Btu of rail fuel averages $6.02 for diesel and would be $1.84 for coal.

For work done at the drawbar, therefore, diesel costs $18.81 per million Btu of energy to the pulling coupler ($6.02 x 1/.32 = $18.81/MBtu at drawbar). For coal, the same cost is $12.27 per million Btu of energy to the pulling coupler ($1.84 x 1/.15 = $12.27/MBtu at drawbar). The fuel cost savings for equal work performed under equal conditions is therefore 34.7 percent. Thus, if an individual railroad were to switch to coal fuel, it could cut its fuel bill by more than one-third.

In 1979, the railroads nationally consumed 4.3 billion gallons of diesel fuel. At 82¢ per gallon, that consumption would cost $3.66 billion including fuel handling. If railroads were to convert to coal fuel and locomotive efficiency were only 15 percent, the same traffic could be hauled for a fuel cost including fuel handling of $2.39 billion, a savings of $1.27 billion, assuming Eastern coal prices.

In unit coal train service where coal locomotive fueling could be done at the mine and eliminate the fuel delivery charge and part of the post-delivery handling costs, then the fuel savings would be greater. For example, if it is assumed fuel handling costs are approximately equal, and assuming $5.87 per million Btu for diesel and $1.58 per million Btu for low-sulfur coal, the fuel savings per million Btu of work done at the drawbar would be about 43 percent. Since coal traffic accounts for such a large proportion of rail traffic [17], a 43 percent savings might apply to a significant fraction of total ton-miles. Thus it is reasonable that the total fuel costs of railroads nationally could drop more than $1.3 billion by converting to coal fuel.

It should be stressed that the savings percentages above are independent of a value of Btu per gross ton-mile. Different railroads experience different figures for Btu per GTM, depending on topography, traffic density, length of haul, size of trains, etc. Average values go from 200 Btu/GTM to 300 Btu/GTM, with the national average being 260 to 265 Btu per GTM in 1979 [17]. For a particular railroad service averaging 200 Btu/GTM, the fuel cost at 82¢ per gallon is $1.16 per thousand gross ton miles ($/KGTM). For a service averaging 300 Btu/GTM, the fuel cost is $1.74/KGTM. A new coal-fired locomotive could reduce the fuel costs of either service by 35 percent. Such a reduction would result in fuel costs of $.75/KGTM and $1.13/KGTM, respectively.

D. Comparative Costs of Diesel vs. New Coal-Fueled Locomotives

Equipment Costs. A new 3000-horsepower diesel locomotive of the four-axle type now costs close to $750,000 and will probably cost about $900,000 in 1982. A new coal-fired steam locomotive design of relatively simple construction as proposed by the designers is expected to cost $1.25 million in 1982 dollars when manufactured in quantities of 200 or more units per year. The coal-fired locomotive is expected to have a maximum drawbar horsepower of about 4000, with the rated drawbar horsepower of 3000 available over a wide range of speeds. Low-speed, continuous pull will be similar to the continuous rating of a four-axle diesel, since automated adhesion control can be applied to a new reciprocating steam engine, unlike traditional steam engines. Hence, in comparison to a four-axle diesel with a shaft horsepower for traction of 3000 and a drawbar horsepower of 2400, the coal-fired locomotive conservatively should be capable of hauling 20 percent more ton-miles per train-hour.* Thus, if well managed, the coal-fueled locomotive fleet could be about one-fifth smaller than the diesel fleet for the same traffic level, making the investment in the coal locomotive fleet about equal to an investment in a new diesel fleet. It is relevant to note here that over two-thirds of the U.S. diesel fleet of 28,000 locomotives is over 10 years old [17]. New coal-fueled locomotives could be gradually phased-in as older diesels are replaced.

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*Ton-miles per train-hour is proportional to drawbar horsepower; TM/TH and DBHP are similar measures of work in different units. For a nominal 3000 horsepower diesel, transmission efficiency of 80 percent in everyday service gives 2400 drawbar hp. The new steam engine could produce 3000 hp at the drawbar over a wide speed range, peaking at 4000 DBHP.

Fuel Handling Costs. Fuel handling costs for diesel locomotives are estimated at about $0.02 per gallon, which includes fuel transportation, fuel storage, fuel loading and fueling equipment repair. The estimated handling cost for coal is about $6.50 per ton, which includes capital costs of extra modular coal packs, railroad costs in loading coal packs at the mine, transportation of loaded coal packs to refueling stations, return of empty packs, crane handling of packs at refueling stations, ash box handling and transportation, and necessary labor. These costs convert to about $0.15 per million Btu for fuel oil and $0.26 per million Btu for coal. Thus the cost of fuel on board (FOB) would be $6.02 per million Btu for diesel fuel at current prices, and $1.84 per million Btu for coal. This is equivalent to a total diesel fuel cost of $0.84 per gallon and a total coal cost of about $47.50 per ton, FOB locomotive. In unit coal train service, however, where coal-fueled locomotives could be fueled directly at the mine, fuel handling costs should be less than the figure above.

Maintenance. The recent Gibbs & Hill report [3] estimates Conrail diesel locomotive maintenance costs at $1.27 per thousand gross ton-miles, in the near term. Time between shop maintenance for diesels averages about 15 days per locomotive on many large railroads. In the late 1940s, the time between shop maintenance was estimated to be approximately 20-25 days, according to experienced railroad shop men. On the Norfolk and Western Railway, steam locomotives were serviced at Roanoke, Va., in such a way as to set records for locomotive availability and reliability. The last valid comparative data between steam and diesel is for 1946, when the New York Central ran an extensive service test between new steam of the time and diesel. In comparable service, both types of locomotives cost the same to maintain, about 35¢ per mile, including allowance for annual heavy shoppings and major repairs [19]. In the present day, advances in chemical treatment of boiler water have greatly reduced maintenance of utility boilers, compared to the 1940s. Such water treatment and water quality control can now be applied to a condensing locomotive, in order to reduce the expected maintenance of both boiler and condensing systems. Compared to new types of diesel locomotives now being considered for the 1990s [1], it is likely that steam locomotives would have lower maintenance costs in that time period. To gain added thermal efficiency, proposed new diesels will have Rankine-bottoming, adiabatic design for ultra-high temperature combustion, etc. Such locomotives will thus have boilers, added pumps, heat exchangers, and bottoming turbines, together with the diesel prime mover and electrical transmission. Such diesels will be much more expensive to maintain than current models.

Track Maintenance. The axle loading of a four-axle diesel locomotive is often as high as 35 tons per axle. Design axle load for a coal-fired locomotive can be 30 tons per axle. Thus the lower axle loading for the coal locomotive should be less damaging. Using proven mechanical principles, the drive train of the coal-fired locomotive can be completely and dynamically balanced, both rotationally and in reciprocation [20]. Together with guiding bogies both fore and aft, the coal locomotive as a vehicle should be relatively easy on the track structure, and perhaps less damaging than current locomotives with high axle loadings and nose-suspended traction motors. There would be no comparison with traditional steam locomotive drive-wheel balance, which was often very poor.

Labor Requirement. The coal-fueled locomotive is planned to take full advantage of the latest control technology, together with the new approaches to reliability of such systems. Preliminary studies indicate that the locomotive can be automatically controlled as to power output, furnance, and steam flow by the use of microprocessor control systems so that the locomotive can be operated with the same size crew now used on diesels, regardless of whether the coal-fired locomotives are operated singly or in tandem. Also, because the microprocessor control must act as a "governor" on the coal locomotive's output, a parallel signal can be generated easily to operate any diesel locomotives in trail. Hence, a single operator can control coal and diesel locomotives mixed together in the same multiple-unit string of engines. Remote coal conveying and stoking apparatus were proved in railroad service in the 1940s and 50s. As to labor involved in servicing, the fuel handling and ash handling systems of the coal locomotive can be designed to virtually eliminate intermediate materials handling, so refueling labor should be about the same as for diesels. Heavy maintenance practices on the coal locomotive should involve similar labor costs, since, according to the designers, a new coal locomotive can be built for the same maintenance philosophy as diesel, to include diesel-type cylinder liners, diesel-type lubrication of pistons and valves, standardized parts, etc., all of which can reduce expected labor cost.

VI. ENVIRONMENTAL ASSESSMENT OF COAL-FIRED STEAM LOCOMOTIVE

It is essential that the locomotive meet all applicable environmental regulations and standards. Environmental regulations dealing specifically with mobile coal-fired steam plants have not been promulgated. Since no such environmental regulations exist, an assessment must be based upon size, design and operating principles to which current regulations apply. Such regulations do exist and they apply to fixed coal-fired steam boilers of size from about 10 million Btu/hr heat-input to the largest size coal-fired utility boiler for electric power generation. Most coal-fired steam locomotives will likely have a heat input rate of about 20 million Btu/hr to approximately 60 million Btu/hr. The coal-fired steam locomotive assessed here has a design input heat rate at full power of about 56 million Btu/hr; thus, it will be comparable to a classification of industrial boilers common in state environmental regulations. A boiler classification is given in table 5.

TABLE 5*

Boiler Class	Heat input rate - Btu/hr
Utility	250 million and larger
Large Industrial	50 to 250 million
Small Industrial	10 to 50 million
Commercial	2 to 10 million

Federal EPA regulations only set the maximum values for each pollutant that is controlled. The states, or pollution control districts within a state, may set regulations more stringent than the federal maximum limits. This means that each state may have its own set of standards which are not necessarily the same as federal standards or the standards of other states. For a fixed power plant, this is no problem because the plant can be designed to comply with local regulations at the construction site. With a mobile power plant, such as a steam locomotive, the standards change as the locomotive crosses state lines or pollution control district boundaries. For this discussion, the authors will use an approximate average value for the pollutant under consideration for the states east of the Mississippi River.

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*Boiler Classification developed by A.F. Galli for use in a State of W.Va. study of boiler conversion.

The environmental assessment of a coal-fired steam locomotive includes a discussion of the ability of the steam locomotive to meet the environmental quality standards for (a) opacity, (b) particulate emission, (c) fugitive dust emission, (d) oxides of nitrogen emmission, (e) sulfur dioxide emission, (f) water pollution and (g) noise emission.

Opacity. Opacity emission regulations are generally limited to 20 percent of the maximum opacity value and can be exceeded for one minute of every hour with maximum opacity no greater than 40 percent. Opacity in the products of combustion (POC) is produced by the presence of smoke, mist and particulates. Smoke in the locomotive will be controlled by its two-stage combustion system, a well-known process. Smoke formed in the first combustion stage is expected to be consumed in the second stage thus preventing its discharge from the locomotive stack. The continuous, regulated feed of an automatic stoker for the locomotive will prevent slugs of smoke from forming which may be too great to be consumed. Particulate content of POC will be reduced by cyclone separators placed before the locomotive stack. The combination of two-stage combustion, continuous regulated automatic stoker firing and cyclone cleaning should yield an opacity value for the locomotive of about 10 percent or less, well within the limits of the applicable regulations.

Particulate Emission. The particulate emission standard for the locomotive is expected to be about 0.4 lb. of solid per million Btu of heat input to the boiler or approximately 20 pounds per hour. This limit can be met by passing the POC through cyclone separators placed before the locomotive stack. A cyclone separator bank designed with a pressure drop of 3 in. water should remove about 85 to 90 percent of the particulate matter from the gas, yielding a POC particulate content of approximately 0.28 to 0.30 lb. solid per million Btu heat input to boiler. This value is well within the limits required by pollution standards.

Fugitive Dust Emission. Fugitive dust emission is that dust which escapes to the surroundings during the normal process of moving solids from one place to another. In the case of the steam locomotive, the fugitive dust emissions occur in (a) transporting coal from source to the locomotive service units, (b) feeding the coal to the locomotive boiler and (c) collection and disposal of ash from the combustion of coal. The fugitive dust emissions from these sources can be virtually eliminated by proper design of a solids handling system for the locomotive.

The planned coal transporting system is based on a closed modular container arrangement. Closed coal hoppers, each holding eleven tons of coal, are filled at the coal mine, placed on flat cars and moved to a locomotive service area. A container-handling crane will take an empty container off the locomotive service unit and replace it with a full one. Each service unit will carry three fuel containers, giving the locomotive 33 tons of fuel -- enough for a refueling range of about 500 miles in normal freight service. The empty containers are then returned to the mine to be refilled. Coal is never handled in the open so that fugitive dust emission from coal handling is eliminated.

The coal feed system for the boiler is a screw-fed, oscillating grate fuel burning system, proved on the Norfolk and Western Railway. The coal flows from the bottom of the coal hoppers into a coal feed screw which conveys the coal to the grate feeder and spreads it uniformly on the grate. This system is completely closed so that dust cannot escape to the surroundings.

Coal ash is collected from the grate and from the cyclone dust collector and is conveyed to a closed ash container holding approximately five tons of ash. This container is then removed from the locomotive and replaced with an empty one at the same time that the locomotive takes on coal and water. Such a system eliminates fugitive dust emissions from ash handling.

Oxides of Nitrogen Emissions. Oxides of nitrogen (NO_x) are always formed when a fuel is burned to provide energy. Combustion processes produce more than 80 percent of the man-made oxides of nitrogen that enter our atmosphere. Increasing the temperature of combustion increases the production of nitrogen oxides and increases pollution. The standards for nitrogen oxides emission have not been enforced by EPA as yet and only tentative standards have been established. The standard for a coal-fired boiler is 0.7 lb. of oxides of nitrogen per million Btu heat input [14].

A boiler using two-stage combustion is planned to eliminate smoke problems and to reduce particulate loading of the flue gas leaving the firing zone. Two-stage combustion should also reduce peak temperature during combustion and thus reduce the oxide of nitrogen content in the flue gas. It is probable that this combustor design will give an oxide of nitrogen content of flue gas that is below 0.4 lb. per million Btu heat input -- a value much lower than that normally produced in a coal-fired boiler.

Data for oxide of nitrogen emission from a diesel rail locomotive are very meager but, in general, diesel engines have a high NO_x concentration in their exhaust. The coal-fired locomotive output of NO_x should be considerably less than that of a diesel locomotive.

Sulfur Dioxide Emission. Federal EPA regulations do not control SO_2 emissions for boiler sizes under 250 million Btu per hour heat input rate but many state environmental regulatory agencies do. It appears that for boilers of about 50 million Btu heat input rate, the allowable SO_2 emission rate approximates 2.5 lb. SO_2 per million Btu heat input rate, which would allow the use of 2.1 percent sulfur high-quality eastern coal (13,000 Btu/lb), for which an ample supply exists. To meet the most stringent state regulations, coal containing no more than 1.5 percent sulfur would be used to fuel locomotives. Fuel price calculations have assumed the purchase of coal for one percent sulfur or less.

ASTM Specifications for diesel fuels recognize three grades of diesel fuels and some railroad companies recognize four grades [15], two of which are used as locomotive fuel. The higher quality locomotive fuel has a maximum sulfur content of 1.0 percent, and the lower quality has a maximum sulfur content of 2.5 percent. Quantities of each grade used and their actual sulfur content are not readily available. It appears that the SO_2 emission from the current diesel locomotive is approximately the same as that of the new coal-fired locomotive, and the switch from diesel power to steam power would not appreciably change the SO_2 emission of the rail transportation system.

Acid rain is becoming an increasing environmental problem, particularly in the Eastern United States. Acid rain is generally blamed on SO_2 emission, but recent evidence indicates that acid rain is due to both SO_2 and NO_x emissions and possibly other pollutants [16]. The two-stage combustion system on the coal-fired locomotive will probably have a lower (SO_2+NO_x) output than a diesel locomotive and could possibly lessen rail transportation's contribution to acid rain. Approximately 320-350 steam locomotives will have the same pollutant output as a 1,000 megawatt electric generating station. The locomotives would not be a point source and the pollutants would rise only about 50 to 100 feet above ground level. The pollutants would not be carried as far as power plant emissions that are carried several thousand feet in the air. This means that the pollution from locomotives would be more dilute, and thus it would probably be removed from the atmosphere faster than power plant emissions. The environmental effect of locomotives on acid rain is expected to be less than the effect of the same amount of pollutants emitted from a power plant.

Water Pollution. The steam locomotive in this design uses approximately one-tenth the water of older designs. The steam from the locomotive is condensed and reused. The locomotive requires about 5000 gallons of water for 500 miles travelled. Blowdown from the boiler amounts to about one percent of this value which means approximately 50 gallons of contaminated water would be discharged. This quantity would have almost no environmental effect on water quality. If necessary, even the blowdown water could be recycled to the locomotive water tank.

Noise Pollution. The noise level of this locomotive should be about the same as that of a diesel locomotive. Draft fans are used instead of steam jets for draft and the redesign of steam cylinders and valves can eliminate most of the noise that was present in older steam locomotive designs. These and other changes would bring the noise level down to approximately that of a diesel locomotive.

REFERENCES

1. Liddle, Sidney, G., Future Propulsion Systems for Railroad Locomotives, Phase B Report, Advanced Diesel Engines and Alternative Fuels, Jet Propulsion Laboratory, California Institute of Technology, December 1979 and April 1980.

2. Marshall, Eliot, "Planning for an Oil Cutoff," Science, July 1980, p. 246f.

3. "Conrail Electrification Feasibility Study," Final Report, Gibbs & Hill, Inc., New York, NY, November 30, 1979.

4. Curtis, C. E., "Picking the Synfuel Winners," Forbes, July 21, 1980, pp. 45-48.

5. "Back to Railroading for a New Era," Business Week, July 14, 1980, pp. 63-70.

6. "Clogging Ports Hamper Export Coal Sales," Coal Age, V. 85, No. 7, July 1980, pp. 15-19.

7. Lansberg, Hans H., Energy: the Next Twenty Years, Cambridge, Mass: Ballinger Publishing Co., 1979.

8. Wilson, Carroll L., Coal: Bridge to the Future, Report of the World Coal Study, Cambridge, Mass: Ballinger Publishing Co., 1980.

9. "Utilities: When It Pays to Switch to Coal," New York Times, July 20, 1980, Sec. 3, p. 6.

10. "Granger Roads Gear Up for Long-Term Growth," Railway Age, V. 181, No. 12, June 30, 1980, pp. 24-30.

11. Strobaugh, Robert and Daniel Yergin, "Energy: An Emergency Telescoped," Foreign Affairs, V. 58, No. 3, Spring 1980, pp. 563-595.

12. Joskow, Paul L., "America's Many Energy Futures," The Bell Journal of Economics, V. 11, No. 1, Spring 1980, pp. 377-398.

13. Levy, Walter J., "Oil and the Decline of the West," Foreign Affairs, V. 58, No. 4, Summer 1980, pp. 999-1015.

14. Energy/Environmental Fact Book, Decision Series by USDOE and USEPA, Bulletin No. EPA-600/9-77-014 (March 1978).

15. Bland, W. F. and Davidson, R. L., Editors. Petroleum Processing Handbook, Section II, McGraw-Hill Book Company.

16. West, Susan, "Acid From Heaven," Part 1 and 2, Science News, Vol. 117, Feb. 2, 1980 and Feb. 16, 1980.

17. Association of American Railroads, The Economic ABZ's of the Railroad Industry, 1980.

18. Coal Week, McGraw Hill, various issues, June-July, 1980.

19. Paul W. Kiefer, A Practical Evaluation of Railroad Motive Power, Simmons-Boardman, 1949.

20. W. E. Dalby, The Balancing of Engines, Longmans-Green, various editions.

21. Stoffels, W., Lokomotivbau und Dampftechnik, Birkhauser Verlag, Basel and Stuttgart, 1976.

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Future Fuels and Engines for Railroad Locomotives

Volume I: Summary

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ABSTRACT

A study was made of the potential for reducing the dependence of railroads on petroleum fuel, particularly Diesel No. 2. The study takes two approaches: (1) to determine how the use of Diesel No. 2 can be reduced through increased efficiency and conservation, and (2) to use fuels other than Diesel No. 2 both in Diesel and other types of engines. The study consists of two volumes; Volume I is a summary and Volume II is the technical document.

The study indicates that the possible reduction in fuel usage by increasing the efficiency of the present engine is limited; it is already highly energy efficient. The use of non-petroleum fuels, particularly the oil shale distillates, offers a greater potential. A coal-fired locomotive using any one of a number of engines appears to be the best alternative to the Diesel-electric locomotive with regard to life-cycle cost, fuel availability, and development risk. The adiabatic Diesel is the second-rated alternative with high thermal efficiency (up to 64%) as its greatest advantage. The risks associated with the development of the adiabatic Diesel, however, are higher than those for the coal-fired locomotive. The advantage of the third alternative, the fuel cell, is that it produces electricity directly from the fuel. At present, the only feasible fuel for a fuel cell locomotive is methanol.

Synthetic hydrocarbon fuels, probably derived from oil shale, will be needed if present Diesel-electric locomotives are used beyond 1995. Because synthetic hydrocarbon fuels are particularly suited to medium-speed Diesel engines, the first commercial application of these fuels may be by the railroad industry.

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INTRODUCTION

Presently, the American railroads ship over 35% of the freight in the United States. This service is second only to pipelines and barges in energy efficiency and serves a wide range of customers. With rapidly increasing transportation fuel costs, the railroads can become an even more important means of freight transportation. Because about 99% of their fleet consists of Diesel-electric locomotives, the railroads are dependent on the supply of Diesel No. 2 fuel. This fuel oil has changed from a relatively cheap and readily available commodity to one having an increasingly limited supply and higher cost. There has been, therefore, a growing interest in improving the fuel economy of locomotives and in finding alternative fuels for use in these same engines.

The objective of this project is, therefore, to assess ways of reducing the dependency of the railroads on petroleum fuels. To achieve this objective, the present state-of-the-art Diesel-electric locomotive and the most promising future engines, transmissions, and alternative fuels are identified, defined, and characterized. Comparisons are made between the current Diesel-electric system, improved Diesel-based systems, and new systems using other engines and power sources. These comparisons should identify the most promising improvements to the Diesel-based systems for short-range applications and the most promising successors, if any, to the Diesel in the longer term.

Because a railroad locomotive has a long service life, roughly 30 years, it will be a long time before any new concept can be incorporated into the fleet in significant numbers. In the short term, retrofit improvements are very important. Improvements can be made to the Diesel-electric locomotive which can decrease its fuel consumption by about 20%. Examples of potential improvements include combustion chamber and fuel system changes, bottoming cycles, improved accessories, turbocompounding, and the adiabatic Diesel engine. Another way to reduce the dependence on petroleum is using non-petroleum based fuels. Recent work in this area indicates that within certain limitations, the medium-speed Diesel engine is a multi-fuel engine. The limitations are that: (1) the cetane number should be above 30, (2) the viscosity should be low enough to prevent pumping problems, and (3) the lubricity should be high enough to maintain fuel system wear at an acceptable level. These limits can be met by a wide range of petroleum and non-petroleum fuels.

In the short term, it is desirable for locomotives to be modified for energy conservation and alternative fuels. In the long term, an assessment must be made as to whether the Diesel-electric is to remain the preferred system. Because of the high capital costs, electrification is attractive only for high traffic density lines. These lines form only a small percentage of the railroad routes in the United States. There is and will continue to be a need for locomotives that carry their own energy supply. Of the alternative engines, gas turbines have not proven particularly energy efficient. Improvements in ceramic components and heat exchangers, however, may change this situation. Certainly, the multi-fuel capability of the gas turbine makes it an attractive candidate. The Stirling engine has the potential for good efficiency but also has significant heat transfer and manufacturing problems. Fuel cells are highly efficient energy conversion systems which produce dc power directly. The size, weight, and fuel requirements of fuel cells are the major concerns in their application for locomotives.

This railroad study was divided into three phases. The first phase established performance and cost methods and baseline data for typical present-day locomotives. The second phase was concerned with Diesel-electric locomotive system improvements and alternative fuels for Diesels. The third phase was devoted to new engine systems and life-cycle cost analyses. Each phase was about 7 months long with a separate informal report being issued.

The results of the various phases of the study were presented to the Review Board for discussion and comment. The Review Board was made up of representatives of locomotive manufacturers, fuel suppliers, operating railroads, universities, and government agencies. The meetings of the Review Board stimulated discussion and comments which have been incorporated into this final report.

CRITERIA

How were the various modifications, engines, and other options selected for study? The basic criterion was: does a proposed approach reduce the petroleum fuel dependency of the locomotive? This question can only be answered when taking a number of factors into consideration. The thermal efficiency of an engine is directly related to its fuel consumption. The availability of a fuel, under certain circumstances, becomes more important than efficiency. Cost is another important consideration which will always be present and frequently is a determining factor. Technical feasibility is as important as cost in many cases. For example, with some alternative fuels, the technical feasibility has been established and the projected costs are not excessive, but the current supply is inadequate and the long-term supply depends on the technical and cost feasibility of the manufacturing method. This is true of some of the synthetic fuels, particularly coal derived liquids.

In the alternative engine area, some proposed engines are designed more for increased power than for increased fuel efficiency. The other extreme is where improving the efficiency can result in an engine that is so large and heavy, or so complex that it is not practical for use on a locomotive. There are definite limits to the width, height, and weight of the locomotive. The criteria can be summed up as follows:

(1) System reliability.

(2) Petroleum savings.

(3) Technical feasibility.

(4) Favorable economics.

(5) Availability of the fuel supply.

(6) Safety.

Other considerations are:

(1) Width restrictions.

(2) Height limits.

(3) Total and per axle weight limits.

(4) Overall length.

(5) Maintenance.

(6) Logistics.

These last two items, maintenance and logistics, are more specifically railroad oriented. With any new engine or modification to an existing engine, there will be changes in maintenance procedures. As a general rule, any additional maintenance should be minimized. An improvement in fuel economy may require an increase in maintenance which must be within the capability of the railroad shops. For some alternative fuels, the logistics of supplying the fuel along the lines may be a deciding factor. The problems associated with the shipping, storage, and handling facilities for an exotic fuel may be enough to eliminate that fuel from consideration even if all other factors are favorable. The alternative fuels are competing with Diesel No. 2 and with each other and there are many factors involved, including site-specific ones. Similarly, alternative engines are competing with the Diesel engine and with other alternative engines.

DIESEL-ELECTRIC LOCOMOTIVE MODIFICATIONS

The present day locomotive Diesel engines are highly developed but there is some room for improvement in the combustion chamber, the valves, and the fuel injection system. These changes are more evolutionary than revolutionary in nature. Among the possible engine modifications examined are increased maximum cylinder pressures, increased turbocharger boost pressures, and reduced piston speeds. A possible three percentage point gain in thermal efficiency can come from increasing the maximum cylinder pressure to 3000 psia. The turbocharger boost pressure could then be increased as well. A four percentage point increase is possible if the boost pressure is increased to three atmospheres. A reduction in piston speed of 37% could result in a net improvement of one and one-half percentage points. If these three modifications were used together, the gain is eight percentage points in thermal efficiency. The loss of power because of reduced engine speed is countered by the increase resulting from the higher cylinder pressures. The engine would be heavier but about the same overall size as the present engine. These changes would require an extensive engine redesign. There is no modification to existing engines that would have a significant effect on fuel consumption except the addition of exhaust heat recovery systems.

Approximately one-third of the energy in the fuel leaves the engine in the exhaust gas. One way of increasing the overall thermal efficiency of the engine system is to recover some fraction of this energy and turn it into useful work. Bottoming cycles are one means of recovering this energy and consist of three main types:

(1) Power generating cycles.

(2) Charge heating cycles.

(3) Fuel reforming cycles.

The power generating cycles convert exhaust energy into useful work through such options as turbocharging, Rankine engine compounding, and Stirling engine compounding. Turbocharging is already in use on many locomotive engines. Retrofitting of turbochargers to existing non-turbocharged engines is possible and, in many cases, desirable. The type of service in which the locomotive is used and the mechanical problems with the engine itself must be considered. Line-haul locomotives would benefit from retrofitting but locomotives used for switching and short-line service are not good candidates for it.

Charge heating cycles use the engine exhaust energy to heat the air, the fuel, or the fuel-air charge, before or after compression. It was found that this type of bottoming cycle is not attractive for locomotive Diesel engine applications.

In fuel reforming cycles, the exhaust energy is used to convert a liquid fuel into a gas mixture that has a higher heating value than that of the original liquid fuel. Direct decomposition and steam reforming are the most attractive of these cycles. Each of these two cycles are suitable only for certain fuels. Direct decomposition is practical only for methanol. Methanol and ethanol can be steam reformed using the exhaust energy from conventional Diesel engines. Steam reforming of hydrocarbon fuels requires higher exhaust temperatures and is only marginally suitable for adiabatic Diesel engines. A variation of this type of cycle is the partial oxidation of the fuel with heat recovery from both the partial oxidation process and the engine exhaust.

The energy efficiency gains which can be achieved using bottoming cycles vary widely. In notch 8, turbocharging results in about a three-percentage-point improvement in thermal efficiency. Depending on the working fluid, the specific engine, and the space limitations, the Rankine bottoming cycle can improve the thermal efficiency by two to five percentage points. The Stirling bottoming cycle can be used only on an adiabatic Diesel engine and can result in a four- to five-percentage point gain.

The fuel reforming cycles are more complex than the power generating cycles. They affect both the engine inlet system and the exhaust system.

The gains in thermal efficiencies are also larger. The direct decomposition of methanol could result in an eight percentage point increase in thermal efficiency. The steam reforming of methanol will yield a five-percentage-point gain and the reforming of ethanol can have a nine-percentage-point gain in thermal efficiency. Partial oxidation reforming is limited to about four percentage points for all fuels. The direct decomposition of methanol is the simplest of the fuel reforming cycles and is nearly the most efficient one as well. The greatest disadvantage to the fuel reforming cycles is the limited number of suitable fuels.

In addition to the modifications of the engine, modifications to the rest of the powertrain must be considered. The auxiliary equipment, the transmission, and the dynamic braking system, all use engine power and affect the fuel consumption of the locomotive as a result.

The auxiliary power used for the equipment blowers, air compressors, radiator fans, and auxiliary generator on a typical 3000-hp locomotive ranges from about 25% of gross engine output in notch 1 to 6% in notch 8. The major items are the equipment blowers and the radiator fans that absorb about 215 hp in notch 8. Improved aerodynamics could reduce this figure by about 8% and the use of demand controls could reduce power by another 5 to 7%. The manufacturers have already made major improvements in this area in the last 3 years.

Present versions of dynamic braking require using the engine to provide power for fans and blowers during braking. The power generated in the dc motors is dissipated in resistor grids. Ideally, it should be possible to supply all of the power needed by the locomotive from the dynamic braking power. Unfortunately, this power is not always in a usable form. The voltage of the power from the motors varies with motor speed and does not match the needs of the blower motors. If the power could be conditioned using modern solid-state devices so that it could be used, then the engine could be operated at low idle during dynamic braking. The savings in fuel is estimated to amount to some 9000 gal per year for a typical 3000-hp locomotive.

The present electric transmission is efficient and there are no changes that could be made that will have a significant effect on fuel consumption. The relative merits of ac versus dc motors in the transmission have little effect on energy efficiency.

The various engine and locomotive modifications are ranked in Table 1. This ranking has many qualifiers attached. For example, the direct decomposition of methanol is a viable option only if methanol is a viable fuel. The Stirling compounded bottoming cycle can be used only with an adiabatic Diesel engine. These options are ranked not only on their efficiency gain but on their costs, complexity, maintenance requirements, and the range of engines to which the options could be applied.

Table 1. Relative Ranking of Diesel Locomotive Modifications

1. Rankine compound bottoming cycle
2. Direct decomposition of methanol
3. Stirling compounded bottoming cycle
4. Increased turbocharger boost pressure
5. Increased maximum cylinder pressure
6. Turbocharger retrofit
7. Accessory power reduction
8. Dynamic braking engine power reduction
9. Reduced piston speed
10. Partial oxidation fuel reforming
11. Steam fuel reforming
12. Electric transmission modifications
13. Leaning out the air-fuel ratio

ADVANCED DIESEL ENGINES

The Diesel engine has been under development for nearly a century and has become an efficient prime mover. This engine, in turn, can be combined with other thermodynamic cycle engines to produce even more efficient systems. These combinations were initially discussed in connection with the bottoming cycles for use with conventional Diesel engines. Advanced Diesel engines are unconventional with multiple cycle engines that can achieve efficiencies well in excess of today's engines.

Turbocompounding an engine is using a turbine in the exhaust system to convert waste energy into power which is added to the crankshaft power. It is not a new concept; turbocompounded spark ignition aircraft engines were built in the 1940s. Turbocompounded truck Diesel engines are currently under development. There are no known instances of its use on locomotive Diesel engines.

A series of Diesel engine changes are shown in Figure 1. Figure 1-a shows a truck or industrial Diesel engine rated at 500 hp, but is equally applicable to four-stroke locomotive Diesel engines as well. The turbocompounded version of this engine shown in Figure 1-b has a rated output power of 581 hp, 16% greater than the base engine rating of 500 hp. More important, the BSFC (brake specific fuel consumption) of the turbocompounded engine is nearly 9% less. Alternately, the thermal efficiency of the engine is three percentage points higher.

Because most of the methods proposed to improve the thermal efficiency of the engine system depend on the use of exhaust gas energy, is logical to try to divert the cooling system heat into the exhaust system. The adiabatic Diesel engine is shown in Figure 1-c. Instead of a cooling jacket, the cylinder is insulated to prevent heat from flowing away from the combustion chamber. Similarly, the cylinder head, valves, and piston crown are insulated. In this configuration, the amount of heat lost to cooling is reduced 13 percentage points to only 17% of the total input

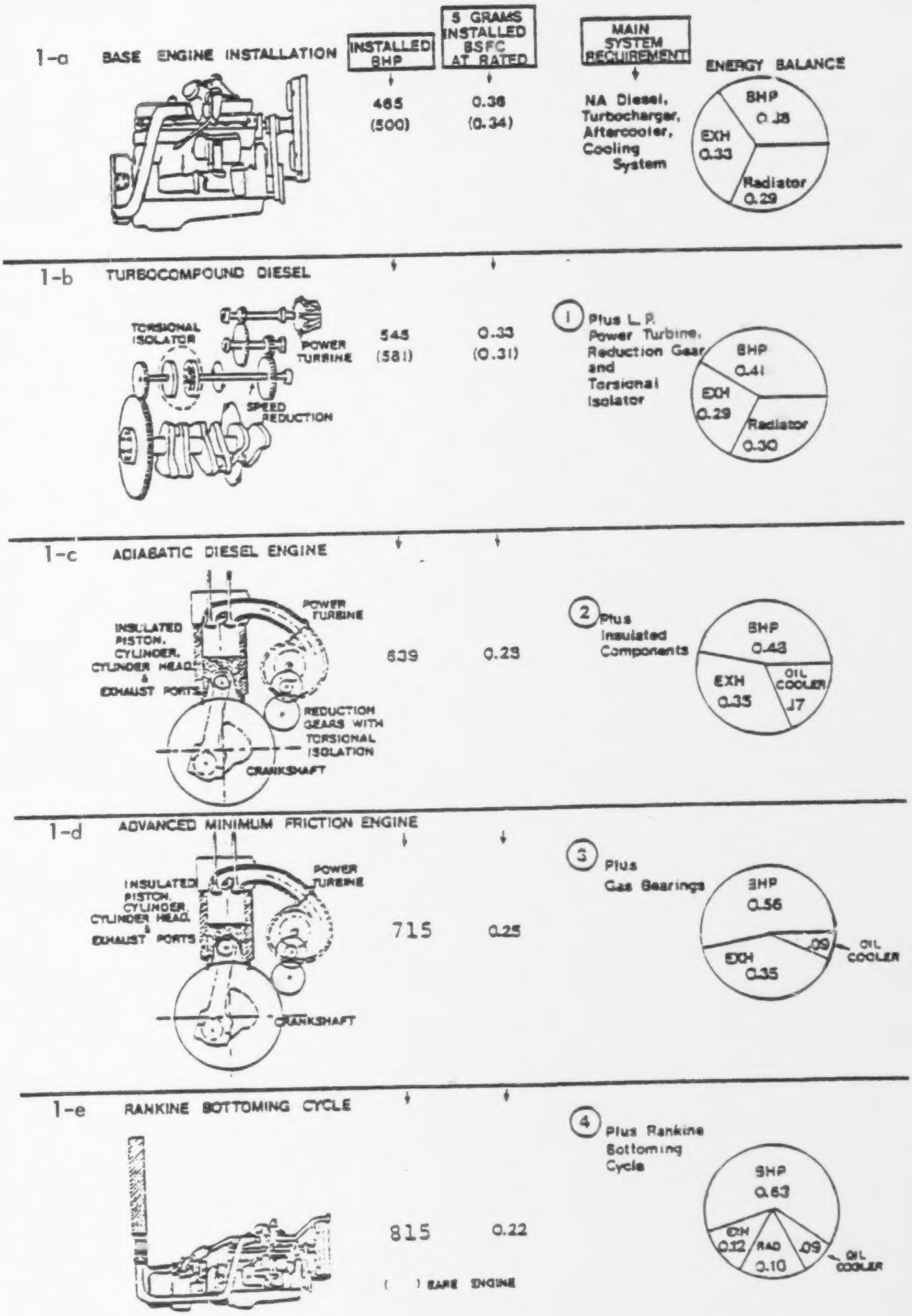

1-a BASE ENGINE INSTALLATION
INSTALLED BHP
5 GRAMS INSTALLED BSFC AT RATED
MAIN SYSTEM REQUIREMENT
ENERGY BALANCE
465 (500)
0.36 (0.34)
NA Diesel, Turbocharger, Aftercooler, Cooling System
BHP 0.38
EXH 0.33
Radiator 0.29
1-b TURBOCOMPOUND DIESEL
TORSIONAL ISOLATOR
POWER TURBINE
SPEED REDUCTION
545 (581)
0.33 (0.31)
① Plus L.P. Power Turbine, Reduction Gear and Torsional Isolator
BHP 0.41
EXH 0.29
Radiator 0.30
1-c ADIABATIC DIESEL ENGINE
INSULATED PISTON, CYLINDER, CYLINDER HEAD & EXHAUST PORTS
POWER TURBINE
REDUCTION GEARS WITH TORSIONAL ISOLATION
CRANKSHAFT
639
0.23
② Plus Insulated Components
BHP 0.48
EXH 0.35
OIL COOLER .17
1-d ADVANCED MINIMUM FRICTION ENGINE
INSULATED PISTON, CYLINDER, CYLINDER HEAD & EXHAUST PORTS
POWER TURBINE
CRANKSHAFT
715
0.25
③ Plus Gas Bearings
BHP 0.56
EXH 0.35
.09 OIL COOLER
1-e RANKINE BOTTOMING CYCLE
815
0.22
( ) BARE ENGINE
④ Plus Rankine Bottoming Cycle
BHP 0.63
EXH 0.12
RAD 0.10
.09 OIL COOLER

Figure 1(a-e). Advanced Diesel Base Power Plants energy. The exhaust gases contain about 42% of the total heat and the exhaust gas temperature has increased by 400°F. The high energy content of the exhaust gas suggests that more than one heat recovery system could be used. The adiabatic Diesel shown in Figure 1-c has two heat recovery systems, turbocharging and turbocompounding. The last system on this figure, Figure 1-e, "Rankine Bottoming Cycle" uses three; the Rankine bottoming cycle, turbocompounding, and turbocharging. The additional heat recovery systems have a marked effect on BSFC and on thermal efficiency. The adiabatic Diesel engine has a thermal efficiency seven percentage points higher than the turbocompound engine and 10 percentage points higher than the base engine.

The walls of an adiabatic engine are very hot. On test engines, they are red hot. As a result, the materials and lubricants used in this engine must be able to withstand the high temperatures and the stresses imposed by Diesel engine operation. Ceramics are, therefore, an integral part of the adiabatic engine design because no other class of materials will stand up to the high temperatures. Designing reliable engine components with ceramics, however, is considerably more difficult than designing them with metallic materials. The failure mode of metallic parts is usually quite predictable but the mode of failure for ceramic parts is less predictable. Thus, to avoid failures, ceramic parts should be stressed low and their quality control be kept high. Some of the ceramics that could be used are:

(1) Hot pressed silicon nitride.

(2) Sintered silicon nitride.

(3) Reaction bonded silicon nitride.

(4) Lithium aluminum silicate.

(5) Aluminum silicate.

(6) Silicon carbide.

The lack of high temperature lubricants is a major problem in developing the adiabatic Diesel engine. There are solutions available, however. One solution is to eliminate lubricants entirely. The minimum friction engine uses this approach. Gas bearings are used in the piston-cylinder liner interface and ceramic roller bearings for the wrist pins, crank pins, and main crankshaft bearings. Solid lubricants would be used for gears, valve guides, rocker arms, and push rod assemblies. One version of the minimum friction engine is shown in Figure 1-d. This version uses only the gas bearing at the piston-cylinder liner interface and uses a conventional oil system for the remaining bearings. As a result, 9% of the input energy goes to the oil cooler. The engine power in this case has increased from 500 hp to 715 hp and the BSFC has dropped to 0.25 lb/hp-hr. The thermal efficiency is 55%, 16 percentage points better than the base engine.

The addition of a Rankine bottoming cycle to the fourth configuration results in an output power rating of 815 hp and a BSFC of 0.22 lb/hp-hr. hp-hr corresponding to a thermal efficiency of 63%. The exhaust gas from this engine system contains only 12% of the input heat. Approximately one-third of the heat wasted by the base engine has been recovered in this engine to produce useful energy.

The gains in efficiency are as impressive as the problems of developing the engine. The ceramic parts needed are larger than any yet made from these materials. A better understanding of the failure modes of ceramics is needed. The reliability of ceramic parts in this kind of application must be established. The savings in fuel, and in fuel costs, possible with the adiabatic engine provides a strong motivating force to solve these problems.

Several unconventional Diesel engines that are not adiabatic Diesels were investigated including the augmented Diesel, the Hyperbar Diesel, and the regenerated Diesel. The augmented Diesel engine is a turbocharged, turbocompounded Diesel engine with a gas turbine type combustor upstream of the power turbine. By controlling the fuel flow to the combustor, an additional 200 to 400 hp could be produced but, the BSFC would be markedly higher. The use of a Rankine bottoming cycle would lower the BSFC but does not result in an engine significantly more efficient than the base Diesel engine.

The Hyperbar Diesel engine is another engine that uses an auxiliary combustor in the exhaust system. It differs from the augmented Diesel engine in that the combustor is upstream of the turbocharger turbine rather than the power or turbocompounding turbine. The turbocharger in the Hyperbar engine has a 10 atmosphere boost rather than the 2 to 3 typical of conventional Diesels. The losses in the system balance the gains in efficiency so that the BSFC and thermal efficiency are nearly equal for a conventional and a Hyperbar engine. The Hyperbar engine, however, would be considerably smaller and lighter.

One unusual engine which does show possible fuel savings is the regenerative Diesel engine. In this engine, part of the engine exhaust energy is transferred to the compressed air before the injection of the fuel. There is a gain in thermal efficiency of about three percentage points but the mechanical complexity plus the additional losses of heat and pressure make the engine impractical.

The various advanced Diesel engines are ranked in Table 2 by their thermal efficiency. The last two are considered to have a zero gain in thermal efficiency. They could have a decrease under certain conditions. The adiabatic Diesel engines show the greatest potential for increased thermal efficiency. Not shown in this table are the partial adiabatic engines which use a combination of ceramic and cooled metallic components. They may be thought of as intermediate steps in the development of an adiabatic Diesel engine but they are practical engines in their own right. It may not be possible to build fully adiabatic engines with the size necessary for a locomotive but a partial adiabatic could still provide a substantial gain in thermal efficiency.

Table 2. Rankings of the New Diesel Engines

1. Adiabatic turbocompound Diesel engine with minimum friction and rankine bottoming cycle
2. Adiabatic turbocompound Diesel engine with rankine bottoming cycle
3. Adiabatic Diesel engine with Stirling bottoming cycle
4. Adiabatic turbocompound Diesel engine with minimum friction
5. Turbocompounded water-cooled Diesel engine
6. Turbocharged water-cooled Diesel engine
7. Regenerated Diesel engine
8. Augmented Diesel engine
9. Hyperbar Diesel engine

The "mature" or "ideal" Diesel engines are also not included in Table 2. These engines are not really practical engines but were conceived to determine the thermal efficiency limits of Diesel engines. One engine is based on a water-cooled engine of essentially conventional design using the various modifications investigated in this study. The maximum thermal efficiency is about 48%, or about eight percentage points more than present engines. The other engine is based on a fully adiabatic engine with all of the modifications, bottoming cycles, and other locomotive changes. The maximum thermal efficiency in this case is 64%, 24 percentage points above today's Diesel engines.

The Diesel engine is capable of much higher thermal efficiencies than present engines if multiple cycle systems are used. A well-developed adiabatic Diesel with two or three stages of exhaust heat recovery will probably be the most efficient heat engine possible. However, the complexity of this engine system must be considered along with the fuel and cost savings.

ALTERNATIVE ENGINES

The Diesel engine is not the only engine that can be used in locomotives. Over the last century and a half, reciprocating steam engines, steam turbines, and gas turbines have all been used. If the railroads' dependency on Diesel No. 2 fuel is to be reduced, it is necessary to examine engines other than the Diesel.

In the realm of alternative engines the principal candidates are gas turbines, steam engines, Stirling engines, and fuel cells. There are numerous variations of these generic engine types. No attempt has been made to explore all of the possible engines but rather to determine the relative merits of the various generic types.

Table 3 lists the principal engine types and the specific versions examined in this study. For this study, the fuel cells are considered engines although, they operate on principles quite different from the

Table 3. Types of Engines

- Diesel engines
  - Conventional with exhaust heat recovery
  - Modified conventional
  - Partial adiabatic
  - Full adiabatic
  - Full adiabatic
  - Adiabatic with exhaust heat recovery
- Steam engines
  - Reciprocating drive
  - Steam turbine-electric
- Gas turbines
  - Open cycle, internal combustion
  - Open cycle, external combustion
  - Closed cycle, external combustion
  - Reacting gas, external combustion
- Stirling engines
  - Liquid fueled
  - Solid fueled
- Otto cycle
  - Stratified charge rotary
  - Naval Academy Heat Balance engine
- Other
  - Fuel-cell
  - Sodium heat engine

other engines. The sodium heat engine, also known as the alkaline metal thermal energy converter, operates on principles different from either the fuel cells or the other engines.

The steam engines or Rankine cycle engines were used for nearly a century and a half by the railroads until they were replaced by the Diesel-electric locomotives. A new steam engine would bear little resemblance to the old engines except that the working fluid in the engine is steam. The biggest change will be in the coal combustion system. The old locomotives at full power could lose half of the coal, unburned, up the stack. The combustion efficiency of a new combustion system would be 90 to 95% in notch 8. To be compatible with existing Diesel engines, the controls of a new steam engine would be by notches rather than the old throttle lever which was continuously variable. Both steam turbines and steam pistons could be used. Each type has its advantages and the type of service in which the locomotive is used is important.

The basic system used by Rankine cycle steam engines is shown in Figure 2, regardless of whether it is a turbine or a piston engine. With new advances in cylinder lubrication and ring materials, the efficiency of the piston engine is approaching that of the turbine at full load and may be better at part load. The system efficiency of these engines will be, at least 13%, and may be as high as 25%.

The gas turbine was used before by the railroads. These old gas turbines were simple cycle, internal combustion engines and had a number of problems, including blade erosion and high fuel consumption. Any new gas turbine should be regenerated. That is, exhaust energy should be used to heat the compressor outlet air, and if coal is used, it would have to be externally fired.

Three types of regenerative gas turbines were examined for use in a locomotive; internal combustion open cycle, external combustion open cycle, and external combustion closed cycle. These three engines are shown schematically in Figure 3. The internal combustion open cycle engine is dependent on liquid or gaseous fuels and because its thermal efficiency is not expected to be as good as that of a Diesel engine, it is not the recommended choice. The external combustion gas turbines can use a wide variety of fuels such as coal, wood, and crude oil as well as other liquid and gaseous fuels. At this time, the closed cycle gas turbine is more attractive than the open cycle.

The Stirling engine has the potential to be more efficient than the Diesel engine. As yet, this potential has not been demonstrated. The Stirling engine is a much more complex engine, both mechanically and thermodynamically, than the Diesel or the other alternative engines examined. In the Stirling, the working fluid is moved between cylinders as shown in Figure 4 or between the top and bottom of the same cylinder. Because it is an external combustion engine, the Stirling can use the wide range of fuels typical of such engines. This fact, coupled with its high thermal efficiency potential makes it a very attractive engine. At present, however, no Stirling engine exists in the size needed for a locomotive. There is a U.S. Department of Energy program at Los Alamos to develop large Stirling engines for stationary power generation applications and this effort may make the Stirling locomotive practical. The problems involved in the development of the engine are formidable and the engine cannot be expected to be in production before the mid 1990s.

Fuel cells are also attractive for locomotive applications in the middle to late 1990s and beyond. They combine high efficiency (50% and above) with simplicity of operation. The fuel is converted into electricity without all the moving parts typical of the Diesel-electric locomotives. The process by which this is accomplished is shown in Figure 5.

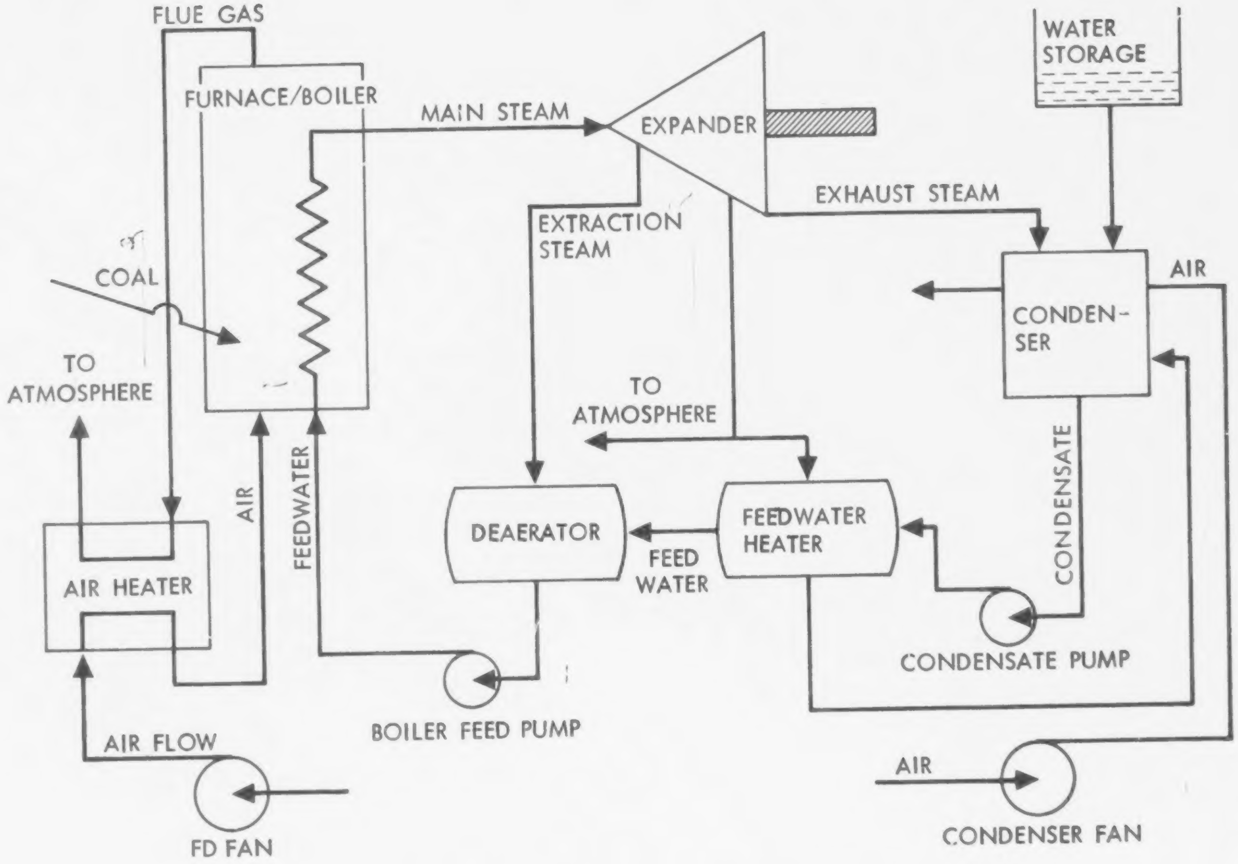
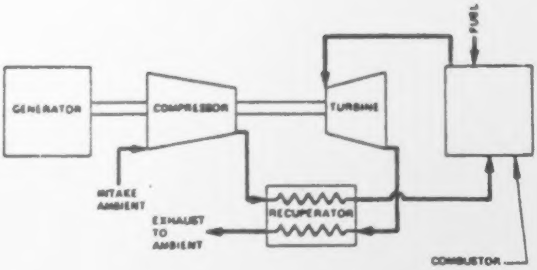
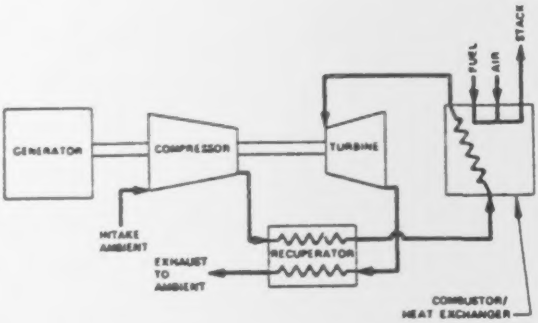


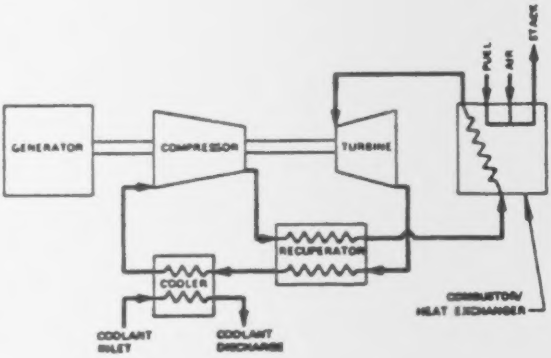
Figure 2. Steam Cycle for Coal-Fired Locomotive



INTERNALLY FIRED OPEN CYCLE GAS TURBINE

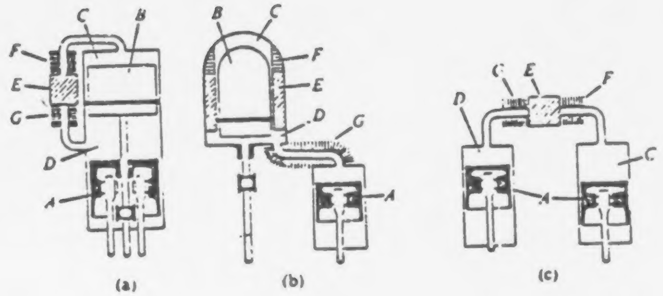


EXTERNALLY FIRED OPEN CYCLE GAS TURBINE



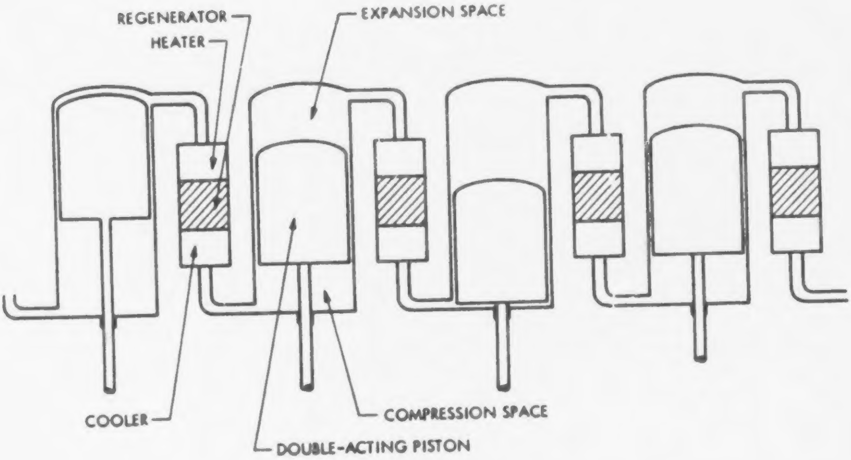
CLOSED CYCLE GAS TURBINE

Figure 3. Single Shaft, Regenerative Gas Turbine Engines



Types of Single Acting Engine Arrangements

(a) Piston-displacer, in the same cylinder
(b) Piston-displacer, in separate cylinders
(c) Two-piston machine



Schematic Representation of a Double Acting, Four-Cylinder Stirling Engine

Figure 4. Stirling Engine Schematics

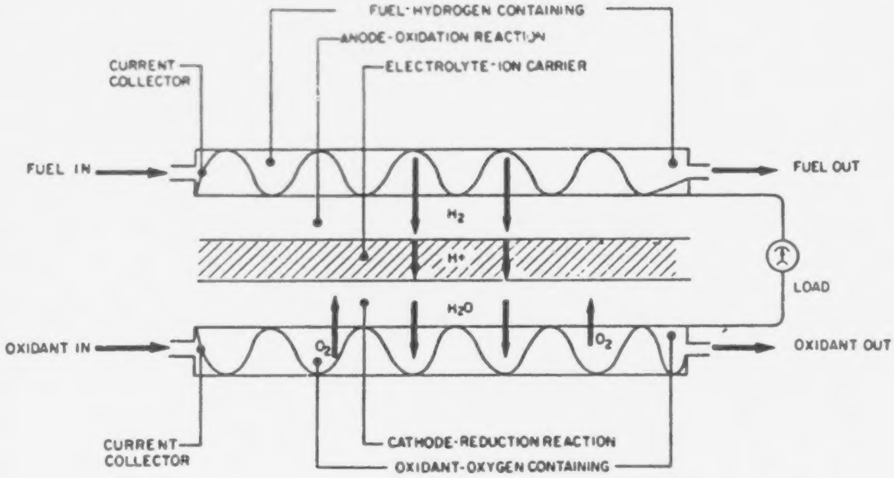


Figure 5. Conceptual Diagram of a Phosphoric Acid Fuel Cell

At present, the only fuel cell sufficiently developed to be seriously considered is the phosphoric acid cell. The only fuel which is attractive for this application is methanol decomposed into a hydrogen-rich gas. This dependence on a single fuel is one of the primary disadvantages of the fuel cell. Experience with the New York City and the Tokyo fuel cell installations for utilities may have a strong influence on the future of fuel cell locomotives.

There were a number of other types of engines examined in the study and an even larger number that received cursory examination. It was not practical to examine in detail more than a small fraction of the possible engine systems. Four which received some attention because of their unusual nature are the Naval Academy Heat Balance engine, the stratified charge rotary engine, the reacting gas Brayton cycle engine, and the sodium heat engine. More than anything, they demonstrate the wide range of possible alternative engines and may indicate the direction of future engine research.

The thermal efficiencies of 18 different engines are shown in Table 4. The engines include Diesel engines with various modifications, advanced Diesels, and the alternative engines. The efficiencies range from 20 to 64%. These efficiencies are for the engine alone in notch 8. System efficiencies (fuel to rail) involve the effects of auxiliary equipment and powertrain efficiency, and are typically about two-thirds of these values. Average system efficiency involves the part load characteristics of the engines and the duty cycle of the locomotives. Average system efficiency values are about half of the figures in Table 4 but vary markedly from engine to engine.

Table 4. Ranking of Engines by Thermal Efficiency

Engine	Notch 8 Thermal Efficiency, %
1. Long term "mature" adiabatic Diesel engine	64
2. Adiabatic turbocompound Diesel engine with minimum friction and Rankine bottoming cycle	59
3. Adiabatic turbocompound Diesel with Rankine bottoming cycle	54
4. Adiabatic turbocompound Diesel with minimum friction	52
5. Adiabatic Diesel with Stirling engine bottoming cycle	51
6. Short term "mature" conventional Diesel engine	50
7. Phosphoric acid fuel cell using methanol	49 (46)[b]
8. Conventional Diesel fueled by directly decomposed methanol	47
9. Advanced Stirling engine using liquid fuels	46
10. Conventional Diesel with Rankine compound bottoming cycle	45
11. Open cycle, internal combustion regenerative gas turbine	42
12. Closed cycle, external combustion regenerative gas turbine[a]	40
13. Present Diesel engine	40
14. Open cycle, external combustion regenerative gas turbine[a]	39
15. Advanced Stirling engine using a fluidized bed combustor	39
16. Advanced stratified charge rotary combustion engine	35
17. Second generation new steam engine	28
18. First generation new steam engine	20(17)[c]

Notes: [a] Efficiency based on shaft power to alternator using ceramic heat exchanger in fluidized bed, turbine inlet temperature is 2250 °F.

[b] Efficiency based on dc output rather than shaft power. Equivalent shaft efficiency will be 49%.

[c] Efficiency based on cylinder output to wheels, equivalent shaft efficiency will be 20%.

If liquid fuels are available, the Diesel and advanced Diesel engines are the best choices for the remainder of this century. Beyond that, the Stirling and fuel cells may be used. The use of coal requires an external combustion engine and, in this case, the gas turbine and steam engines are the likely choices with the Stirling engine as another possibility.

ALTERNATIVE FUELS

A different approach to reducing the dependency of the railroads on petroleum-based Diesel No. 2 fuel is the use of non-petroleum fuels and petroleum fuels other than Diesel No. 2. These alternative fuels may be alcohols, coal and liquid fuels derived from coal, oil shale derived hydrocarbon fuels, vegetable oils, and inorganic fuels such as hydrogen. In addition, there are the blends, slurries, and emulsions that can be made from these fuels and from petroleum-based fuels. The number of candidate fuels is over 30 and there are a large number of blends, slurries, and emulsions. The total number of possible fuels is in excess of 100.

Alternative fuels have been used by the railroads in the past. Wood and coal were used by steam locomotives for well over 100 years. Several railroads, including Southern Pacific and Union Pacific, have used residual oils in Diesel engines at various times.

A list of candidate fuels for use as straight fuels is presented in Table 5. These fuels are divided into groups based on their source except for the alcohols and for hydrogen and ammonia. The emulsions, solutions, slurries, and blends listed in Table 6 can be used in addition to the straight fuels.

The use of an alternative fuel in an engine affects more than just the engine itself. The storage of the fuel on the locomotive and at a refueling terminal must be considered. Safety hazards, toxicity and material compatibility are as important as viscosity and heating value. Because of the wide range of fuels to be evaluated, a suitable method of comparison had to be devised. The method that was implemented is based on the concept of functional properties rather than the physical and chemical properties normally used. Functional properties are defined as properties of the fuel that are related to engine, locomotive, or railroad system functions. These properties are not rated on an absolute basis, but on a relative basis. Because locomotives now use Diesel No. 2 in a Diesel engine, it is important to know how each of the alternative fuels compare to this fuel.

For each combination of a fuel and a functional property, a relative value is determined by comparing it to Diesel No. 2. This value is then multiplied by the weighing factor of the particular functional property to get an individual score. The individual scores are totalled to get the final score for the fuel. The ranking of the fuels is based on these final scores which have no other significance than as a means of ranking.

Table 5. Candidate Fuels for Diesel Engines

Petroleum

- Diesel No. 2
- Gasoline
- Light distillate
- Naphtha
- Lube stock
- Broadcut fuel oil
- Jet A
- Kerosene
- Methane
- Butane
- Propane
- No. 4 fuel oil
- No. 5 fuel oil
- No. 6 fuel oil

Coal

- Powdered coal
- Coal derived gasoline
- Coal derived distillate
- Solvent refined coal

Oil Shale

- Oil shale distillate
- Oil shale gasoline

Inorganic

- Hydrogen
- Ammonia

Alcohols

- Methanol
- Ethanol

Vegetable Oils

- Cottonseed oil
- Corn oil
- Peanut oil
- Olive

Tar Sands

- Syn-crude

Table 6. Slurry, Emulsion and Blend Fuels

Slurry fuels

- Coal in Diesel fuel
- Carbon black in Diesel fuel
- Petroleum coke in Diesel fuel
- Flour in Diesel fuel
- Cornstarch in Diesel fuel
- Wood Fibers in Diesel fuel
- Coal in water

Petroleum Blend Fuels

- Gasoline in lube oil
- Heavy aromatic naphtha in Diesel fuel
- Gasoline in Diesel fuel

Emulsion Fuels

- Water in Diesel fuel
- Methanol in Diesel fuel
- Ethanol in Diesel fuel

The 22 functional properties used in this study are listed in Table 7. This list is applicable for all types of fuels and engines. For example, ignitability is related to cetane no. in a Diesel engine, and has little significance in a gas turbine engine. The weighing factor used for each functional property would vary with the type of engine system. The properties are divided into four main categories depending on whether they affect combustion, engine operation, logistics and storage, or maintenance and safety.

The rankings of the 41 fuels, slurries, emulsions and blends for application in Diesel engines are shown in Tables 8 and 9. Similar tables have been generated for other engines. The rankings of the 18 slurries, emulsions, and blends are separate from the straight fuels. The highest ranked fuel in Table 8 is the petroleum based broadcut fuel oil. The second highest ranked fuel and the highest ranked non-petroleum fuel is oil shale distillate. The lowest ranked of the straight fuels is ammonia. In general, the emulsions, slurries, and blends have scores well below many of the straight fuels. For example, the highest ranking slurry, 20% coal in Diesel No. 2, has a score of -13 which corresponds to tenth place in the straight fuels list.

Not all of the fuels investigated are suitable as long-term replacements. Three basic ways to use these fuels are as emergency, extender, and replacement fuels. Emergency fuels are intended for short term usage in the absence of the regular fuel. In choosing emergency fuels, there should be little or no engine or locomotive modifications required. Generally, proper blending of the fuel will eliminate any need for modification. Blends of petroleum products, synthetic hydrocarbons and alcohols are well suited to use as emergency fuels. Increased maintenance may be

Table 7. Functional Properties

Combustion Related Properties

- Ignitability
- Flame speed
- Power density
- Combustion rate
- Smoke

Engine Operation

- Energy density
- Pumpability
- Boiling point
- Pour point
- Vaporization
- Lubricity

Logistics and Storage

- Future cost
- Future availability
- Water reactivity
- Tank volume
- Special tankage
- Stability

Maintenance and Safety

- Special equipment
- Compatibility
- Lubricant reactivity
- Toxicity
- Fire hazard

Table 8. Final Ranking of Fuels Relative to Diesel No. 2

Fuel	Combustion	Engine Operation	Logistics and Storage	Maintenance and Safety	Total Score	Final Rank
Gasoline	-13	-1	0	-14	-28	12
Naphtha	-6	+4	+3	-2	-1	6
Light distillate	0	+4	+3	0	7	2
Lube stock	-26	+9	-3	+2	-18	11
Broadcut fuel oil	0	0	+15	-2	13	1
Jet A	0	0	+3	-2	1	5
Kerosene	0	+3	+3	-2	4	3
Methane	-1	-14	-7	-15	-37	15
Butane	+3	-6	+4	-15	-14	9
Propane	+5	-6	+4	-15	-12	8
No. 4 fuel oil	-11	-2	-3	0	-16	10
No. 5 fuel oil	-33	-13	-3	-5	-54	16
No. 6 fuel oil	-44	-11	0	0	-55	17
Methanol	-14	-20	-4	-26	-64	18
Ethanol	-14	-20	-12	-19	-65	19
Powdered Coal	-60	-34	+44	-21	-71	20
Coal derived distillate	-11	-3	+13	0	-1	6
Coal derived gasoline	-12	-4	-5	-10	-31	13
Oil shale distillate	-11	-3	+20	-2	+4	3
Oil shale gasoline	-12	-4	-5	-10	-31	13
Hydrogen	-10	-41	-13	-39	-103	22
Ammonia	-17	-41	-27	-38	-123	23
Cottonseed oil	-37	-11	-51	+14	-85	21

Table 9. Final Ranking of Fuel Slurries, Emulsions, and Blends Relative to Diesel No. 2

Fuel	Combustion	Engine Operation	Logistics and Storage	Maintenance and Safety	Total Score	Final Rank
Diesel fuel Slurries						
20% Carbon black	-22	-15	-6	0	-43	17
20% Petroleum coke	-11	-9	-3	0	-23	10
20% Flour	-6	-14	-12	0	-32	13
20% Cornstarch	-6	-14	-12	0	-32	13
20% Wood fibers	-11	-19	-6	0	-36	15
20% Coal	-16	-1	+4	-6	-19	6
Diesel Fuel Emulsions						
10% Water-6% emulsifier	-6	-3	+3	-4	-10	2
30% Water-10% emulsifier	-9	-15	+7	-4	-19	6
10% Methanol-30% surfactant	-12	0	-12	0	-24	12
30% Metahnol-30% surfactant	-7	-13	-22	-11	-53	18
10% Ethanol-4% surfactant	-12	0	-9	0	-21	8
30% Ethanol-12% surfactant	-7	-13	-19	-2	-41	16
Petroleum Blends						
30% Gasoline in lube oil	-10	-1	0	0	-11	3
70% Gasoline in lube oil	-11	-10	0	-2	-23	10
64% Heavy aromatic naphtha in Diesel	-12	0	0	0	-12	4
35% Heavy aromatic naphtha in Diesel	-12	0	0	0	-12	4
50% Gasoline in Diesel No. 2	0	-5	0	-2	-7	1
80% No. 6 fuel oil in Diesel No. 2	-16	-6	0	0	-22	9

necessary with these fuels and their long-term use is not usually recommended.

An extender fuel stretches the supply of Diesel No. 2 when it is inadequate. In general, the use of extenders may be either long- or short-term. One requirement of an extender fuel is that it can be mixed with Diesel No. 2 and that a stable mixture results. In some cases, such as methanol, an emulsifier is required.

Because extenders are used for a longer period of time than emergency fuels, the requirements for engine compatibility are greater but more extensive engine modifications are permitted. The changeover from Diesel No. 2 to a replacement fuel can be facilitated if the replacement fuel can first be used as an extender. The fraction of the replacement fuel can be gradually increased until it becomes the only fuel.

A replacement fuel totally replaces Diesel No. 2 either by taking its place in a Diesel engine or by its use in an alternative engine. Coal used in an external combustion engine is one such fuel. As a replacement fuel in Diesel engines, oil shale distillate is the most attractive of the non-petroleum fuels. No modifications to the engine or locomotive are required. It is well suited to the medium speed Diesel engine and the prospects for an adequate supply at a competitive price looks good for the year 1995.

For non-Diesel engines, coal is the best fuel when used in an external combustion engine system. The supply is ample and stable. Its cost is expected to remain well below that of petroleum or synthetic hydrocarbon fuels in the foreseeable future. The technology of coal combustion has improved in the last 10 years to a point where it now appears feasible to build a clean, efficient coal-fired locomotive.

In the future, railroads will probably use more than one fuel in their fleet of locomotives. The use of one fuel in the past was convenient and economical, but now, economics and supply problems dictate a multi-fuel future.

COAL COMBUSTION

Coal is probably the most attractive of the alternative fuels from the cost and availability standpoint. The biggest drawback to its use is that it is a difficult fuel to burn cleanly and efficiently. The biggest problem facing the coal-fired locomotive is the development of a combustion system that will burn the coal in an efficient and environmentally acceptable manner and that will fit into a locomotive.

There are a wide variety of ways to burn coal. These can be grouped into four main classes: direct open-chamber, direct in-bed, gasification, and liquefaction. Direct open-chamber combustion burns coal by the injection of powdered coal or by the use of a grate. Direct in-bed combustion is the complete burning of the coal in a bed of some other material. The bed may be a fixed bed or a fluidized bed and the bed material may be either inert or one that reacts with a combustion product. Coal gasification is an indirect combustion system. The reactions are in two main steps: (1) the production of the coal gas, and (2) the combustion of the gas with air. The two reactions are separated in both time and space. Liquefaction is a similar process except that the intermediate product is a liquid rather than a gas. The coal liquid is not likely to be consumed immediately and may, in fact, be further processed before it is used.

Of these four classes, only the direct in-bed and the gasification types are likely to be used on a locomotive in which raw coal is carried as the fuel. Coal gasification was used in the steam engine with reciprocating drive and a direct in-bed system in the form of a boiling fluidized bed for the steam turbine-electric locomotive. It was also used for the external combustion gas turbine and one of the Stirling engines.

Both the fluidized bed and the gasification combustors exist in more than one form. There are at least seven different fluidized bed combustors and at least ten coal gasifier systems. Which ones are best suited for use in a locomotive will require a much more detailed analysis than is possible in this study. It is also possible that more than one system is suitable for this application.

LIFE-CYCLE COST ANALYSIS

Many of the new engines are technically feasible for use in line haul locomotives. Many of the fuels are also technically feasible for use in these engines. The economic feasibility of both the engines and the fuels, however, must be considered. The relative economic merits of these engines and fuels have been ranked in terms of their life-cycle costs which include capital, fuel, maintenance, and operational costs.

The detailed method of calculation used in this analysis is based on a costing methodology developed by the Jet Propulsion Laboratory and documented in The Cost of Energy from Utility-Owned Solar Electric Systems, JPL Report ERDA/JPL-1012-76/3, June 1976. Although this model was originally developed for utility applications, it is actually much more general. By using financial data from cooperating railroads and from the open literature, the model provides a present value lifecycle cost consistent with the accepted practices of engineering economics.

The life-cycle cost of a specific locomotive represents the present value of all of the cost incurred in purchasing and operating a locomotive, including a normal rate of return on equity. More specifically, the calculation implies that all capital, operations, maintenance, and fuel costs have been accounted for. Factors such as taxes, depreciation schedules, rates of inflation, and system service life are also considered. All of the individual must costs for all of the locomotives must be as consistent as possible.

The fundamental equation of the annualized life-cycle cost methodology is:

$$\underline{AC} = FCR \times CI_{pv} + CRF_{k,N} (OP_{pv} + MNT_{pv} + FL_{pv})$$

The terms are defined as:

$\underline{AC}$ = Levelized annual life-cycle cost

FCR = Fixed charge rate

CI_{pv} = Present value of all capital investments

$CRF_{k,N}$ = Capital recovery factor based on capital cost k and service life N

OP_{pv} = Present value of operating costs

MNT_{pv} = Present value of maintenance costs

FL_{pv} = Present value of fuel costs

To have consistent cost figures for all of the cost areas, it is necessary to have a single cost reference. For this study, it is the Wholesale Price Index. Values of the index for the past 20 years were used to predict values for the next 20 years. From these values and historical data, cost correlations in terms of constant dollars were established and cost predictions for specific fuels, maintenance, and other parameters were computed. These predictions were then modified depending on whether the particular cost was expected to increase in cost at a lower rate than inflation, at the same rate, or at a higher rate. Once all of the costs were calculated, they were combined to compute the annualized life-cycle cost for each engine-fuel combination being considered. Eighteen fuels and 18 engines were used for the final evaluation.

In addition to the fuel price predictions developed at JPL, predictions made by the U.S. Department of Energy and Data Resources, Inc. were also used for comparison. These predictions were much more limited, using only distillate fuel and coal. The predictions of cost versus time for the two fuels and the three models are shown in Figure 6. The life-cycle costs using these three models are shown in Table 10. Although there are considerable differences between the predicted fuel prices, the life-cycle costs are reasonably close. The ratio of the life-cycle cost of the Diesel locomotive to that of the coal-fired gas turbine locomotive for the three models are very close, with only a 6% difference between the high and low values. The life-cycle cost is not overly sensitive to the details of the fuel price predictions. The other cost areas also show a similar insensitivity. The absolute dollar values will vary widely, but the ratio of the life-cycle costs for any two locomotives or fuels, tends to be nearly constant.

Table 11 shows the life-cycle costs for 15 fuels used in a conventional present day Diesel engine modified as necessary to use the specific fuel.

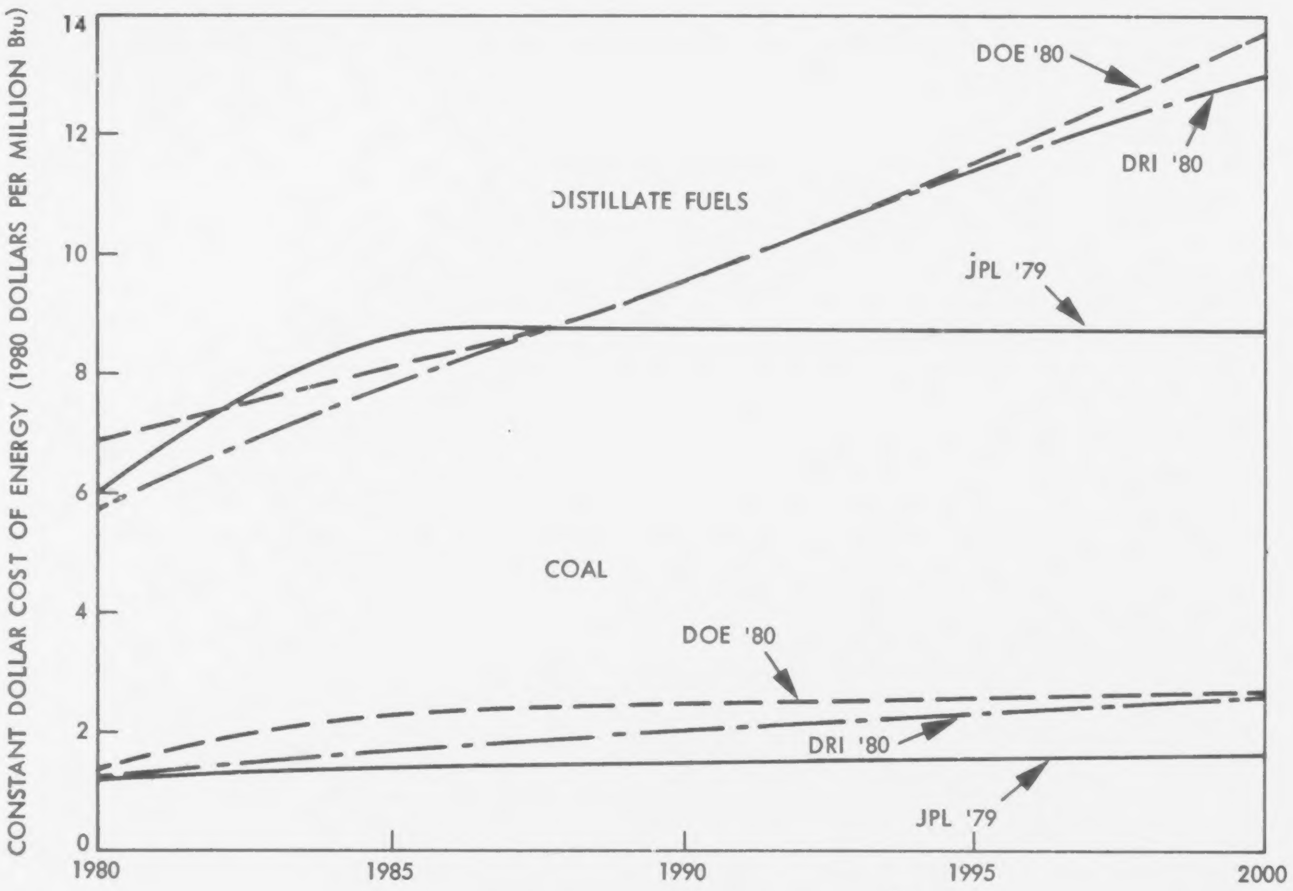


Figure 6. Predicted Fuel Prices to the Year 2000

Table 10. Comparisons of Annualized Life-Cycle Costs Using JPL, DOE, and DRI Fuel Projections

Conventional Diesel Using Distillate Fuel

Data Source	Life-Cycle Cost
JPL	$1,175,000
DOE	1,293,000
DRI	1,263,000

External Combustion Closed Cycle Gas Turbine Using Coal

Data Source	Life-Cycle Cost
JPL	$554,000
DOE	648,000
DRI	608,000

Ratio of Life-Cycle Cost for Distillate to that of Coal

Data Source	Ratio
JPL	2.12
DOE	2.00
DRI	2.08

Differences between the Life-Cycle Cost for Distillate and that of Coal

Data Source	Difference
JPL	$1,175,000 - 554,000 - $621,000
DOE	1,293,000 - 648,000 - 645,000
DRI	1,263,000 - 608,000 - 655,000

Table 11. Ranking[a] of Fuels for Conventional Diesel Engines by Annualized Life Cycle Costs

Ranking	Fuel	Annualized Life-Cycle Cost
1	Oil shale syn-crude	$1,028,000
2	Oil shale distillate	1,036,000
3	Propane	1,047,000
4	No. 6 fuel oil, low sulfur	1,090,000
5	Broadcut fuel oil	1,104,000
6	Coal derived gasoline	1,114,000
7	N- Butane	1,137,000
8	Coal derived distillate	1,139,000
9	Methanol	1,150,000
10	Oil shale gasoline	1,173,000
11	Diesel No. 2	1,175,000
12	Gasoline	1,215,000
13	Methane	1,232,000
14	Hydrogen	1,569,000
15	Ammonia	2,024,000
16	Ethanol	2,675,000

[a] All fuels used in conventional Diesels modified to accept the fuel and dual-fueled when needed.

In some cases, a fuel tender must be used and its costs are included. Except for the last three fuels; hydrogen, ammonia, and ethanol, the rest of the fuels are nearly the same in cost, differing from that of Diesel No. 2 by less than 13%. Because the uncertainty of the calculation is probably near 10%, it can be concluded that the costs are basically equal. The use of an alternative liquid fuel in an engine does not reduce costs but does increase availability. Even if one fuel was in short supply, another one might be available.

The ranking of 24 engine-fuel combinations are shown in Table 12. In this table, there are marked differences in life-cycle cost, ranging from a low of $523,000 to a high of $1,196,000. There are some engine-fuel combinations which are higher but they are not economically attractive and they have, therefore, not been included in these lists. One example is an internal combustion gas turbine using ethanol. A first generation steam engine using Diesel fuel is another. Oil-fired steam engines were used by some railroads before the switch to Diesel engines. Today, the cost of operating such an engine would be extremely high.

Four of the engine-fuel combinations in Table 12 are shown in Table 13 with the life-cycle costs broken down into the four main cost areas. The present Diesel-electric locomotive using Diesel No. 2 is a high fuel cost, low capital cost unit. At the other extreme, the closed cycle gas turbine using coal is a low fuel cost unit with relatively high capital and maintenance costs. The low fuel costs more than counterbalance the other costs to a point where the closed cycle gas turbine locomotive has a life-cycle cost less than half of that of the Diesel-electric unit. Table 13 is useful in evaluating the sensitivity of the life-cycle costs to changes in fuel or other costs. A doubling of coal prices relative to Diesel prices would add $157,000 to the gas turbine life-cycle cost bringing it up to $711,000.

The effect of a reduction in the locomotive usage per year can be estimated from Table 13. The operating, maintenance, and fuel costs are essentially linear functions of the locomotive usage. For the Diesel-electric locomotive, a reduction of 50% in yearly usage as measured in locomotive hp-hr at the rail would reduce the operating, maintenance, and fuel costs by 50% from $1,032,000 to $516,000. The capital cost is unaffected so the total life-cycle cost is $659,000 per year. The operating, maintenance, and fuel costs for the gas turbine locomotive is $351,000. Cutting the usage to half reduces these costs to $175,500 and the life-cycle cost is then $378,500. The ratio of life-cycle costs of the Diesel to the gas turbine was 2.12 and it declined to 1.74 when the yearly usage was cut in half. The ratio approaches one when the ton-mileage is about 15% of the original figure of 4,700,000 hp-hr at the rail per year. The coal-fired locomotive is most cost effective in those applications where locomotives use a lot of fuel but the total route usage is not enough to warrant electrification. For switch engines and most branch line service, the Diesel engine is the better choice.

Table 12. Ranking of Engines by Annualized Life-Cycle Costs

Engine	Fuel	Annualized Life-Cycle Costs
Closed cycle, external combustion regenerative gas turbine	Bituminous coal, western mine mouth	$523,000
Open cycle, external combustion regenerative gas turbine	Bituminous coal, western mine mouth	527,000
Advanced Stirling engine using liquid fuels	Bituminous coal, western mine mouth	548,000
First generation steam engine with reciprocating drive	Bituminous coal, western mine mouth	549,000
Closed cycle, external combustion regenerative gas turbine	Bituminous coal, national average price	554,000
Open cycle, external combustion regenerative gas turbine	Bituminous coal, national average price	559,000
Second generation new steam turbine engine	Bituminous coal, western mine mouth	564,000
Advanced Stirling engine using fluidized bed combustor	Bituminous coal, national average price	577,000
Second generation new steam turbine engine	Bituminous coal, national average price	608,000
First generation steam engine with reciprocating drive	Bituminous coal, national average price	615,000
Long-term "mature" Diesel engine	Oil shale distillate	750,000

TABLE 12. (Cont'd)

Engine	Fuel	Annualized Life-Cycle Costs
Adiabatic turbocompound Diesel Engine with minimum friction and Rankine bottoming cycle	Oil shale distillate	$793,000
Adiabatic turbocompound Diesel with Rankine bottoming cycle	Oil shale distillate	818,000
Adiabatic turbocompound Diesel with minimum friction	Oil shale distillate	840,000
Phosphoric acid fuel cell	Methanol from coal	859,000
Adiabatic Diesel engine with Stirling bottoming cycle	Oil shale distillate	870,000
Advanced Stirling engine using liquid fuels	Oil shale distillate	931,000
Four-stroke turbocharged Diesel engine using directly decomposed methanol	Methanol from coal	940,000
Short-term "mature" Diesel Engine	Broadcut fuel oil	977,000
Open cycle, internal combustion regenerative gas turbine	Oil shale syn-crude	1,029,000
Turbocharged water-cooled Diesel with Rankine bottoming cycle	Diesel No. 2	1,101,000
Phosphoric acid fuel cell	Hydrogen	1,118,000
Turbocharged water-cooled Diesel engine (standard)	Diesel No. 2	1,175,000
Stratified charge rotary combustion engine	Oil shale distillate	1,196,000

Table 13. Fractions of the Annualized Life-Cycle Costs

	Capital	Operating	Maintenance	Fuel	Total
Diesel-electric using Diesel No. 2	143,000	26,000	112,000	894,000	1,175,000
Adiabatic Diesel with M.F. and R.B.C. using oil-shale distillate	137,000	26,000	112,000	518,000	793,000
Steam Turbine using national average price coal	189,000	32,000	162,000	225,000	608,000
Closed cycle, external combustion gas turbine using national average price coal	203,000	32,000	162,000	157,000	554,000

NOTES: All locomotives are assumed to be production versions

R.B.C. - Rankine Bottoming Cycle
M.F. - Minimum Friction

Substantial savings can be accrued by the use of coal-fired locomotives in heavy duty service. The type of engine used in the coal-fired locomotive has little effect on the life-cycle costs but has a secondary effect on the amount of coal which has to be handled and the amount of ash for disposal. The facilities required for fuel handling, fuel storage, and waste disposal were not included in this study. They should be included in future studies of coal-fired locomotives.

SUGGESTIONS AND RECOMMENDATIONS

One of the purposes of this study is to provide suggestions and recommendations on areas where research and development efforts are needed. There are six areas that warrant further investigation. They are:

(1) Partially and fully adiabatic Diesel engines.

(2) Coal combustion systems for locomotives.

(3) Fuel cell requirements for locomotives.

(4) Synthetic hydrocarbon fuels.

(5) Operations.

(6) Emergency fuels.

Novel engine designs will be necessary to make the best use of the adiabatic concept and of the present ceramics capabilities. Exhaust heat recovery systems must be developed if the adiabatic Diesel is to be used to its fullest. Substantial government support will be required for these engines because of the high risks and long development times involved.

The development of a clean and efficient coal combustion system has a moderately high risk and a fairly long development time which will need government support. The rest of the locomotive, including the engine, has a low risk and could be funded by industry. The coal-fired locomotive is a project suited to joint government-industry involvement.

The fuel cell is not yet at a point where a demonstration project is warranted. At this time, the research should be aimed at defining the operating environment and the power requirements of the locomotive so that they can be included in future fuel cell development. The next stage, the development of a demonstration fuel cell locomotive could be started in 3 to 5 years provided methanol is, or appears to be, a viable fuel and that experience with large fuel cells like the New York and Tokyo installations is favorable. The fuel cell project, like the adiabatic Diesel, should be primarily by government support. The risks are fairly high.

If existing Diesel engines are used in the 1990s and beyond, it will be necessary to have a source of synthetic hydrocarbon fuels. That source will probably be oil shale. Oil shale distillate is more suited to th medium speed Diesels such as those in locomotives than to the high speed Diesels in trucks and cars or to the gas turbines in aircraft. The producers of oil shale fuels will need a stable market for their products especially in the first few years of operation. The railroads are a logical market. The oil shale fuel should be blended at first with Diesel No. 2 and only later be used as a straight fuel. The research necessary to support such a program is probably within the realm of the railroad and the oil shale industries with a minimum of government support.

Fuel savings are only partially related to the components in the locomotive. How the locomotive is used is another area for savings. The railroads have already made gains in fuel savings in the operations area and are continuing to do so. Research into fuel savings through operational changes are needed and are best accomplished by the railroad industry.

Emergency fuels is an area, like operations, where much has already been accomplished. The research in this area must be completed and documentation written so that the information is widely available. During the next 10 years, until alternative engines and fuels are available, the railroads will be extremely vulnerable to disruptions in their fuel supply. The emergency fuels could alleviate some of the effects of such disruptions.

CONCLUSIONS

The type of engine that will be used in locomotives of the future depends almost entirely on the type and cost of the available fuel. Petroleum fuels are expected to be available for a number of years but both the cost and demand for these fuels will continue to rise. The demand for middle distillate fuels such as Diesel No. 2 will probably grow at a faster rate than that of other petroleum fuels primarily because of the increased use of Diesel powered automobiles in the U. S. and abroad. Coal is expected to be readily available in the U. S. for many years and although coal prices are expected to rise, they are not expected to rise as rapidly as the petroleum fuel prices. Of the non-petroleum fuels, oil shale distillate is the one most likely to be used in the next 20 years. It appears to be economically competitive at today's (early 1981) petroleum prices. Availability is still a problem because full scale commercial processing plants have yet to be built. It is likely that they will be built during this decade. Distillate fuel is suitable for medium speed Diesel engines and the railroads may be the first large scale users of this fuel. Methanol from natural gas is also a likely fuel because the supply of natural gas is much larger than it was thought to be 3 to 5 years ago. Methanol and middle distillate fuel from coal are much further in the future with little prospect of large scale commercial production before the end of the century.

The Diesel engine will be the dominant traction power source for the railroad for, at least, the rest of the century. Blends of oil shale and petroleum distillates will probably be used in the 1990s and beyond the year 2000. Coal-fired locomotives will probably be in service by the late 1980s and in growing numbers in the 1990s. They are not expected, however, to form more than 20% of the fleet within this century. The engine used with coal is expected to be some type of steam engine in the late 1980s gradually shifting to some form of gas turbine in the 1990s.

Beyond the year 2000, the fuel cell and the adiabatic Diesel may enter the fleet. In any case, the railroads can be expected to use a variety of fuels and engines in service by the end of the century. This change from a single fuel to multiple fuels will complicate operations but will also free the railroads from depending on liquid fuels which will still dominate the truck, aircraft, and passenger car transportation systems.

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